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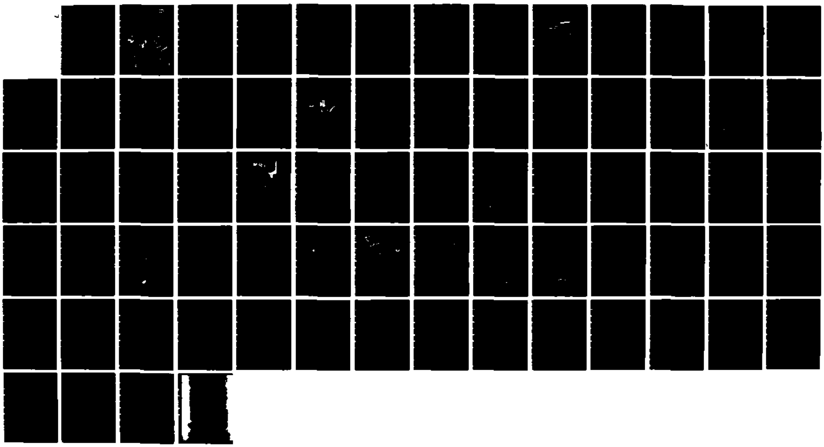

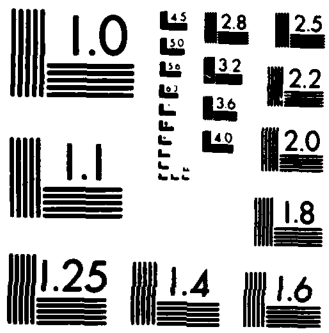

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Special Report 84-14

May 1984

US Army Corps
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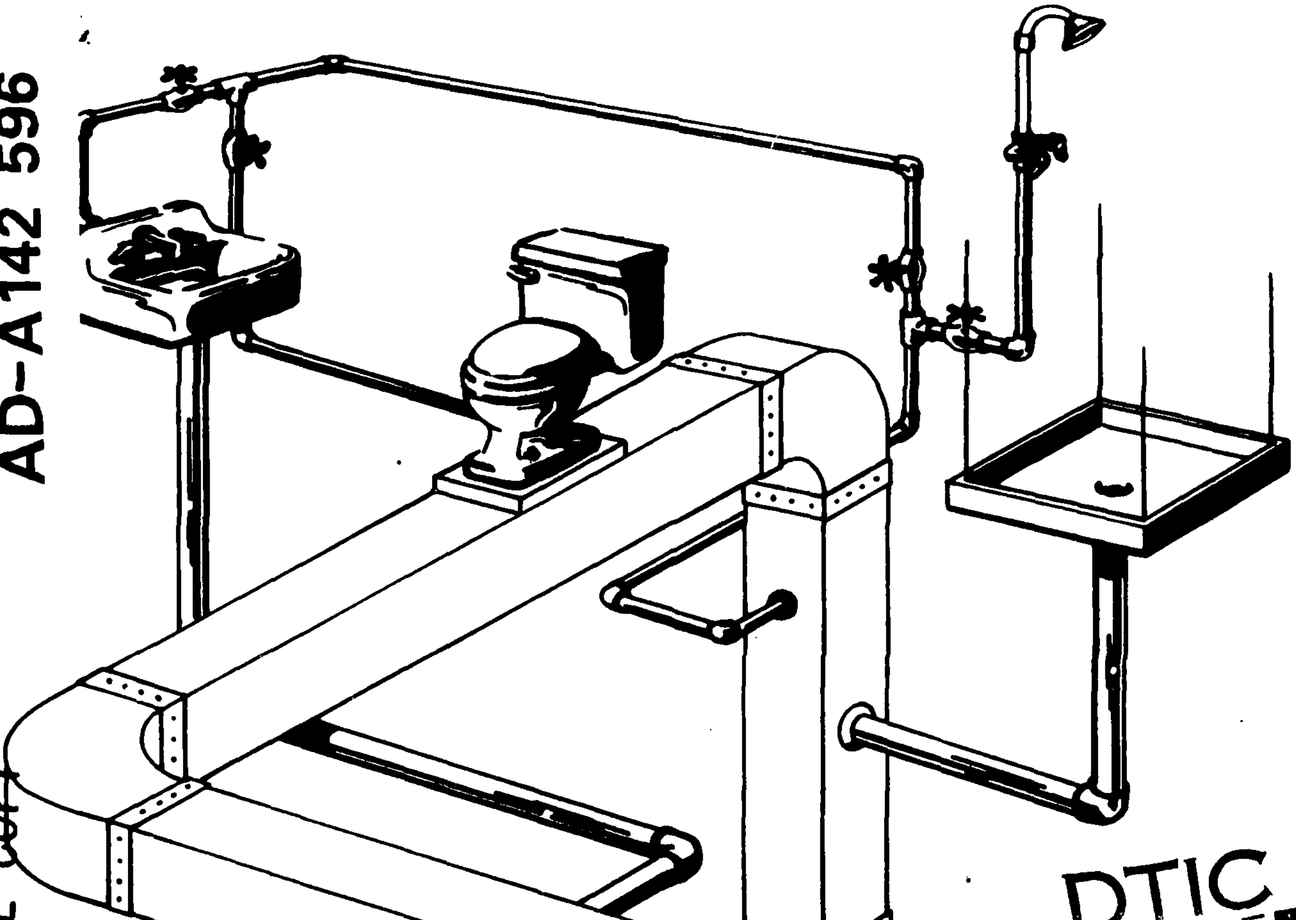
Cold Regions Research &
Engineering Laboratory

On-site utility services for remote military facilities in the cold regions

S.C. Reed, W.L. Ryan, J.J. Cameron and J.R. Bouzoun



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Utility services (water, sewer, solid wastes) for small, remote military facilities in cold regions require special considerations. This report presents concepts and criteria for the planning and preliminary design of internal and external utility systems. Also included are some thermal aspects for design of these water and wastewater systems.

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PREFACE

This report was prepared by Sherwood C. Reed and John R. Bouzoun, Environmental Engineers in the Civil Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory; Dr. William L. Ryan, Director of Engineering, Ott Water Engineers Inc., and formerly Director of Facilities Construction for the U.S. Public Health Service in Alaska; and James Cameron, a consulting engineer with long experience in the design of utility services for the federal government of Canada, the Northwest Territories, and several provinces.

Funding for this activity was provided by DA Project 4A762730AT42, Design, Construction, and Operations Technology for Cold Regions; Task D, Cold Regions Base Support: Design and Construction; Work Unit 002, Utilities Services for Remote Military Facilities and Operations in the Cold Regions.

Technical review of this report was provided by Dr. E.D. Smith and R. Scholze of USACERL, R. Sletten of USACRREL, and S.L. Kistner of USAEHA.

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ON-SITE UTILITY SERVICES FOR REMOTE MILITARY FACILITIES IN COLD REGIONS

S.C. Reed, W.L. Ryan,
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INTRODUCTION

Military activities in cold regions often require isolated buildings or other remote facilities such as guard, communication, and pump stations, and training and recreational facilities. These may be permanently occupied by a small group, intermittently occupied by the same personnel, or used by transient and/or widely varying numbers of people. In all cases, adequate utility services for water supply and waste management must be supplied. In many cases connection to central utility networks for water and sewage may not be possible or economical, so utility services must be provided on site.

This report describes on-site systems that are potentially applicable to remote sites in cold regions. These systems range from completely independent on-site water supply and waste disposal to buildings with independent internal systems that depend on vehicles for water delivery and ultimate waste disposal. The information and criteria presented were derived from successful experience in Alaska, Canada, Greenland, and northern states in the contiguous United States. Wherever possible this report presents "generic" concepts. The mention of any commercial product is intended as an example, not as an endorsement, and the possible omission of some concepts was not intentional. The reader should use this report as a starting point for planning and design, not as the sole source of technical information on the subject. The technology for on-site systems is developing rapidly, with new approaches and proprietary devices emerging frequently. As a result, it is expected that this report will be expanded and updated at regular intervals.

WATER SUPPLY

The basic concerns for on-site water supply systems are essentially the same as for large-scale networks and community systems. Protection of health

is the fundamental purpose, and this requires a reliable water source, adequate water quality, and safe delivery, storage, and distribution. Criteria for large-scale systems can be found in U.S. Army (1982), USEPA (1979), and Alter (1969). This report is only concerned with the unique features and special requirements for the development of on-site water systems.

Water Sources, Quality, and Treatment

The traditional surface and groundwater sources used for community systems also have potential for remote on-site use if economics favor their development. For a single remote building the costs involved will limit the feasible depth of wells or the construction of surface impoundments or complex intake structures. However, because of their small size and the relatively low demand placed on them, on-site systems can often take advantage of water sources that would not be adequate for a community supply, including springs, rainwater collection, and shallow wells in marginal aquifers. Another significant advantage is that water conservation measures tend to be more effective for on-site systems than for large community systems, since the occupants are more directly responsible for their own water supply and can therefore recognize the benefits of conservation more easily.

Natural springs are relatively common in the sub-Arctic and can be developed for an adequate on-site water supply. A spring housing (Fig. 1) physically protects the spring and the quality of the water, but it does not provide a significant amount of storage. If storage is needed, it is usually provided within the building or in a tank. Thermal elements, such as insulation on the cover and insulation and heat tape on the overflow pipe, while not shown on the figure, are essential if winter operation is expected. In aquifers with marginal productivity, the use of a perforated pipe in the water-bearing strata is suggested. In higher productivity aquifers, simpler construction is possible and the spring housing then only needs to be an open-bottom container with impermeable walls. A variation of the construction shown in Figure 1 can be used as a small-scale infiltration gallery next to rivers and streams.

Rainwater can be collected and stored as a seasonal or a supplemental water source. It is a limited source since most precipitation in the arctic and subarctic falls as snow in the winter months. In central Alaska, for example, the rainfall in the warm months of the year averages about 16 cm: a minimal water usage of 10 L/capita/day would require a catchment surface area

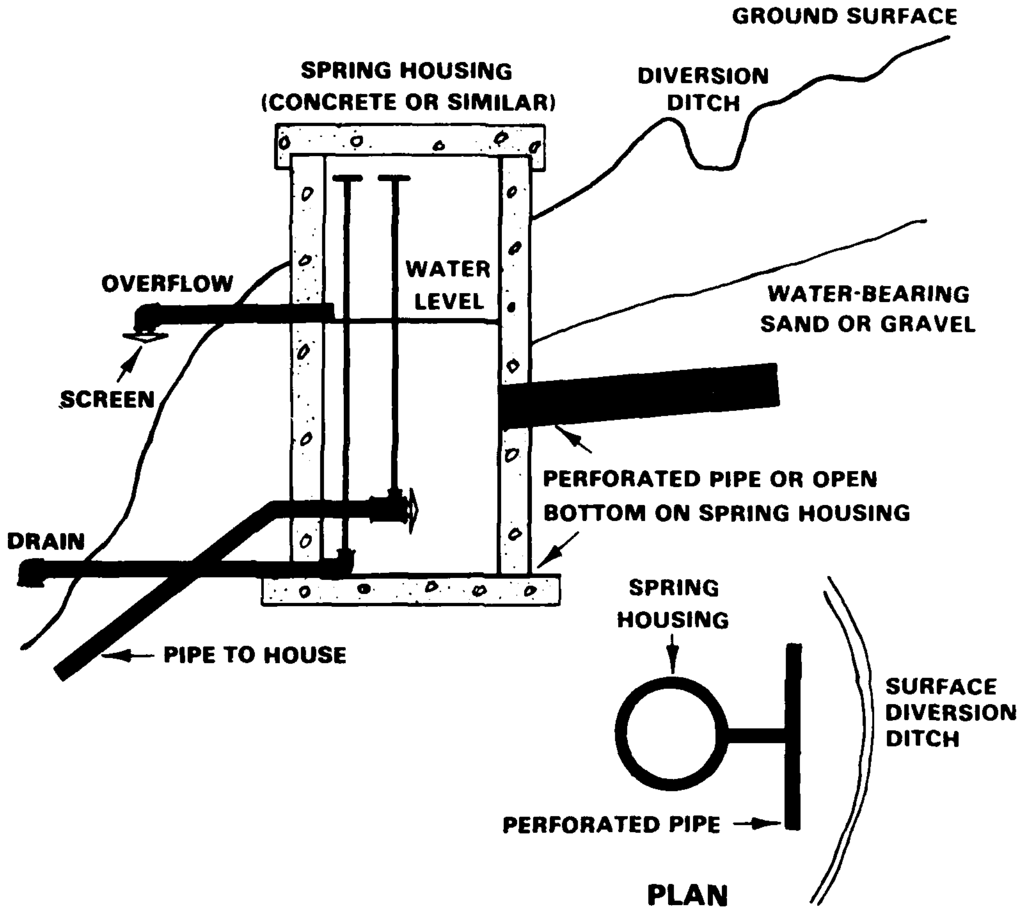


Figure 1. Small on-site spring construction.

of 23 m^2 per person to supply the annual needs. The following equation can be used to determine the catchment area:

$$A = \frac{(q)\ (N)\ (d)}{10(P)} \tag{1}$$

where A = catchment area required (m^2)

q = daily water usage (L/capita/d)

N = number of people

d = number of days water service is required (d)

P = annual rainfall at the site (cm).

The concept is most feasible for schools and similar isolated structures with a relatively large roof area and limited water needs. Figure 2 illustrates the design concepts for a rainwater collection cistern. (The roof washer box must be drained after each rainfall event.)

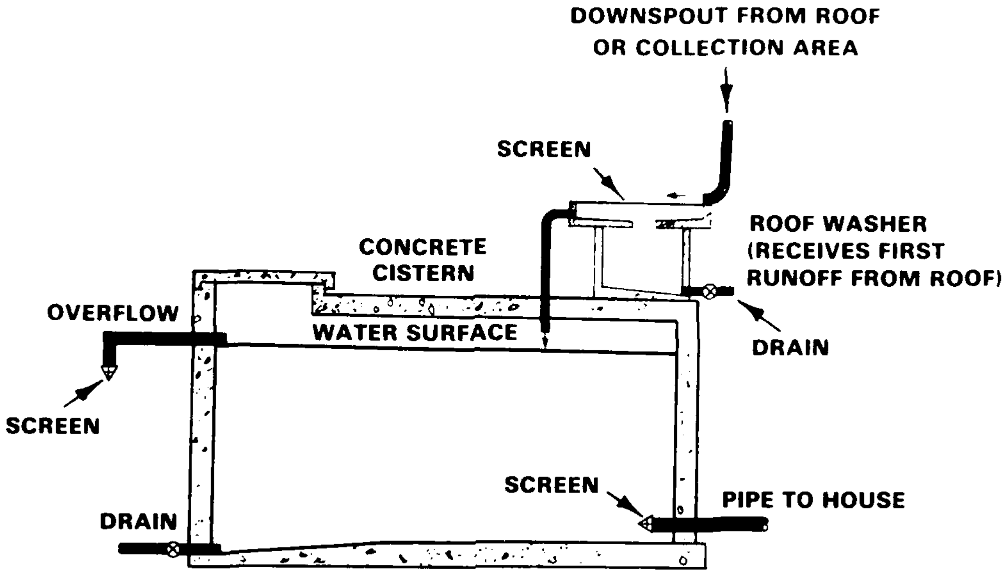
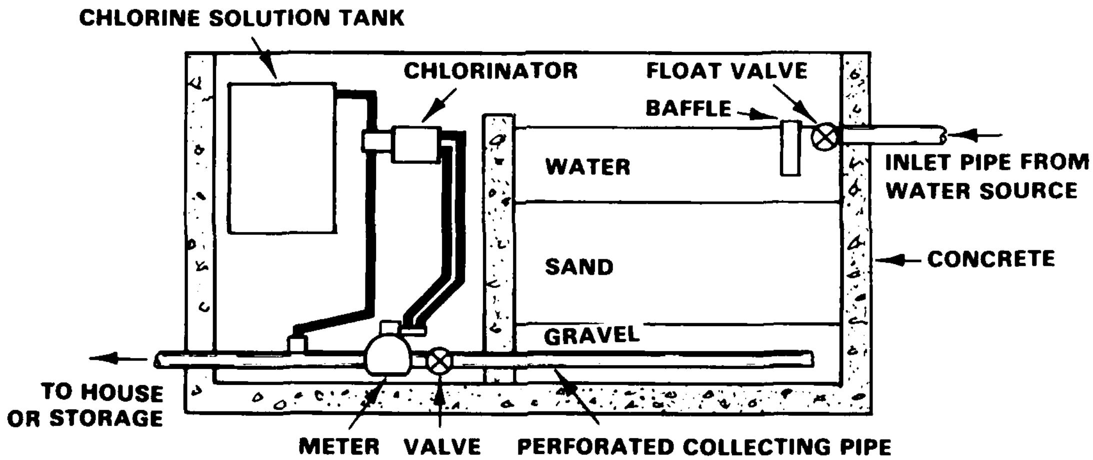


Figure 2. Rainwater collection with a cistern.



FILTER AREA	1 m^2 PER 0.3 m^3/d
SAND LAYER	51 cm DEEP, EFFECTIVE SIZE 0.3 mm
GRAVEL LAYER	10 cm DEEP, 3–10 mm, THEN
	10 cm DEEP, 19–32 mm

Figure 3. Filter-chlorinator for surface water and rainwater sources.

It is prudent to filter and disinfect collected rainwater or water obtained from other on-site surface sources such as ponds or streams. Figure 3 illustrates the basic design concepts for a simple gravity filter and chlorination system for on-site use. Chlorination could be done with solution feeders, as shown, or by hand on a batch basis.

Snow melting is a possible on-site water source in winter, and successful systems for individual homes have been reported (Coutts 1976). The snow collection can be labor intensive and the energy requirements for melting are usually too expensive unless a heat source that would otherwise be wasted (exhaust gases, chimneys) can be utilized. The DEW-line stations on the Greenland ice cap harvest snow with a drag line bucket as their only water source and use a diesel-fueled snow melter to provide about 200 L/capita/day for the station personnel (Reed and Tobiasson 1968). The water yield from melted snow or ice depends on the density of the original material. Fresh loose snow might only have a density of about 0.25 gm/cm^3 and a water yield of about 250 L/m^3 (2 gal/ft^3) of snow. Ice typically has a density of 0.8 to 0.9 g/cm^3 with a comparably higher water yield. Some compaction of the snow occurs during harvesting, so a typical water yield would be about 400 L/m^3 (3 gal/ft^3). About 3 L of diesel fuel would be required per m^3 of snow (at 0°C) if the snow melter were 100% efficient. At these DEW-line stations, that would require about 750 L (198 gal) of diesel fuel per person per year just for snow melting. The energy and labor involved make it obvious that snow melting should only be considered as a last resort or as a standby emergency or back-up system.

Most of the DEW-line stations obtain water from fresh-water lakes, ponds, and streams. On the arctic coastal plain small lakes and ponds occur over 50 to 80% of the total area. Most of the ponds are quite shallow (less than 1 m) and typically freeze solid every winter. The largest lakes are seldom more than 6 m deep. Even if the pond or lake does not freeze solid, the thick ice formation has an adverse effect on the quality of the remaining water. If a facility is to be occupied during the winter in these locations and if surface waters are identified as the potential water source, site investigation and planning must consider the wintertime status of the water body and the depth of ice that will occur. In the worst case that may require filling storage tanks during the summer months for winter use.

Prediction of the ice thickness that will occur is necessary for proper location of water intakes and for estimation of water quality beneath the ice

in relatively shallow ponds. A preliminary estimate of the depth of ice can be obtained with:

$$d = m\sqrt{F_I} \qquad (2)$$

where:

d = depth of ice (cm)

m = coefficient dependent on climatic factors (i.e. wind, snow cover, etc.) See Table 1.

F_I = freezing index for the location (°C·d)

Example: Determine maximum potential ice thickness on a small pond on the arctic coastal plain. Assume F_I = 6000 °C·d

$$m = 3.2 \text{ (from Table 1)}$$

$$d = (3.2)\sqrt{6000} = 248 \text{ cm}$$

In this case the potential depth of ice exceeds the actual depth of most ponds on the arctic coastal plain, so there would be no liquid water available from late winter until after spring thaw.

In the Arctic, most of the annual precipitation is in the form of snow. Although the total precipitation is low, advantage can be taken of windy conditions to induce snow drifting in the watershed of a pond or reservoir. Collection of the melting snow can then augment the summer water supply. At Barrow, Alaska, it was shown that at least 10,000 L of water was collected for every meter of 1.5-m-high snow fence, with the fences about 75 m apart (USEPA 1979).

Surface streams can be turbid in the summer months due to glacial melt, and both streams and ponds can be contaminated by animals, birds, or human

Table 1. m coefficients for determining ice thickness (USEPA 1979).

m Coefficient ($cm/°C^{1/2}·d^{1/2}$)	Site condition
3.2	Maximum for ice not covered with snow
2.8	Windy lake with no snow
2.6	Medium size lake with moderate snow cover
2.1	River with moderate flow
1.6	River with snow on top of ice
1.0	Small river with rapid flow

activity in the watershed. The quality of water in flowing streams tends to improve during the winter since there is little or no surface runoff or glacial meltwater entering the stream. The water quality in shallow lakes and ponds tends to deteriorate in the winter due to the concentrating effect of the ice. If ice is formed at relatively slow rates it will be composed of essentially pure water molecules and most of the suspended and dissolved matter originally in the water will be rejected and will accumulate in the remaining unfrozen liquid. In the practical case there will always be air bubbles and microscopic inclusions of unfrozen water remaining in the ice, so rejection is not 100% efficient. Research in western Canada with natural freezing of brackish ponds indicated that the ice contained about 20% of the salts that were in the original unfrozen water (Fertuck 1969).

If the 20% is adopted as a rule-of-thumb and an assumption is made regarding the density of the ice (say 0.8 g/cm^3), it is possible to estimate the concentration of a substance in the remaining liquid for a particular thickness of ice, depth of pond, and the original concentration of the same substance in the original unfrozen water. It is possible to avoid repetitive calculations by normalizing both sides of the equation:

$$\frac{\text{concentration in liquid under the ice}}{\text{original unfrozen concentration}} = f\left(\frac{\text{ice thickness}}{\text{original pond depth}}\right)$$

or:

$$C = f(I)$$

where

C = concentration increase (%)

I = ratio of ice thickness to pond depth

The boundary conditions for this equation are:

when $I = 0$, then $C = 1$, since there is no ice and no concentration effect

when $I = 1$, then $C = \infty$, as the concentration increases in the last drop of water just before it freezes.

With relatively pure water, I can in fact be equal to 1 and the pond would freeze solid. In the practical case it is unlikely that the pond would be a useable water source if I exceeded 0.8. Adopting that as the upper limit, the following expression can be developed to estimate the concentration increase:

$$C = 1 + 1.72\ I^{(1.56)} \tag{3}$$

where:

C = concentration increase = C_f/C_o

$I = \dfrac{\text{ice thickness}}{\text{pond depth}}$

C_f = final concentration

C_o = initial concentration

Figure 4 can be used for graphic solutions of this equation.

Example: Assume a 2-m-deep pond in central Alaska (freezing index 2000°C·d), with a sulfate concentration of 150 mg/L when the pond is not frozen. Determine the maximum potential depth of ice and the sulfate concentration in the remaining liquid.

From Table 1, m = 3.2, so

$$d = (3.2)\sqrt{2000} = 143 \text{ cm and}$$

$$I = \frac{143}{200} = 0.715$$

$$C = 1 + 1.72(0.715)^{(1.56)} = 2.02$$

The final concentration, C_f, is

$$C_f = (C)(C_o) = (150)(2.02)$$
$$= 303 \text{ mg/L}$$

That would exceed the allowable limit of sulfate for drinking water of 250 mg/L, so the water would be an unacceptable source from late winter until spring thaw.

Groundwater tends to be more consistent in quality and quantity than surface sources and has a slightly higher temperature than surface waters during the winter. However, in central Alaska, groundwater sources often contain significant quantities of iron and other minerals as well as naturally occurring organic compounds that make treatment difficult. Because there are no specially designed units commercially available for the unique water treatment problems of cold regions, it is necessary to use conventional equipment that was designed for use in temperate zones.

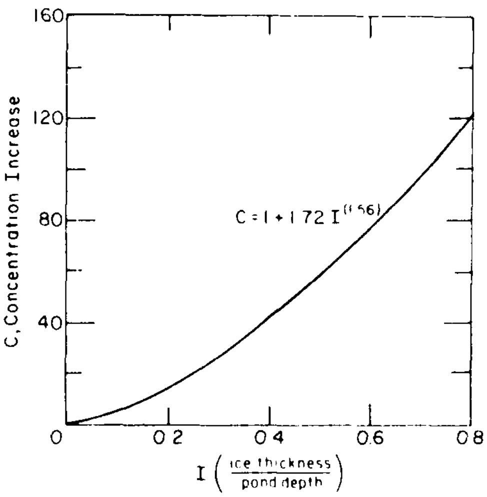


Figure 4. Concentration increase of substances in liquid remaining under an ice cover in shallow ponds.

This includes water softeners, pressure filters often combined with a potassium permanganate chemical feed for iron removal, disinfection equipment, and reverse osmosis units for demineralization. Buildings served by truck delivery systems should not incorporate individual treatment units since it is more economical to utilize a centralized water treatment system.

Most of the DEW-line stations utilize packaged, multimedia pressure filters. These are automated with time-switch control for service, backwash and rinse. Where very turbid water is expected, the use of these filters can be preceded by a centrifugal separator for gross solids removal. Diatomaceous earth filters are also used at remote locations and operate at rates comparable to the multimedia pressure filters. Ceramic filter tubes or cartridges have also been used in portable and fixed installations; they require a regular cleaning of the outer tube surface to maintain filtration efficiency.

Water Quantity

Typical design values for individual daily water usage are given in Table 2. These range from 10 L/capita/day for self-hauled water to 150 L/capita/day for a dwelling with a well and a conventional septic tank disposal system (typical civilian designs assume 6 persons per dwelling in Alaskan arctic villages and 5 persons per dwelling in the Canadian Northwest Territories). Systems dependent on vehicle haul are not constrained by availability of water at the source but rather by the size of the in-house water and waste tanks and the frequency of water delivery and waste pick-up. In many of these communities, there are central facilities for laundry and bathing, so on-site water is only needed for personal consumption, cooking, and possibly waste disposal (with low- or no-water-use toilets). In these cases, 10-15 L of water per capita per day should be adequate. At Galena, Alaska, for example, there are community facilities for laundry and showers with individual water and waste tanks in each of the 50 homes. The average household water consumption is 1440 L/month. This usage rate would only require three to four stops per month by the water truck to keep the 700-L in-house water tank reasonably full.

Usage rates and related design criteria for remote military facilities in cold regions will have to comply with the specifications and guidance in the appropriate manuals and regulations. However, these allowances tend to overestimate the actual needs and usage at remote locations and may as a result increase the cost of project development.

Table 2. On-site water usage (USEPA 1979).

	Water supply system	Liters/person/day Average	Typical range
1.	Self-haul from watering point	10	5-25
2.	Truck delivery		
	a) non-pressure water tank, bucket toilet, and community facilities for laundry and shower	15	5-25
	b) non-pressure water tank, bucket toilets, no community facilities	25	10-50
	c) non-pressure water tank, wastewater holding tank, no community facilities	40	20-70
	d) pressure water system, low water use toilet, waste holding tank and community facilities for laundry and shower	30	15-50
	e) pressure water system, low water use toilet, waste holding tank, no community facilities, and other water-conservation features	60	30-90
	f) pressure water system, conventional toilet, waste holding tank, truck delivery	100	70-140
3.	Well or spring with septic tank/seepage pit	150	80-250
4.	Conventional community pipe distribution system (gravity sewers)	200	100-400
5.	Conventional community pipe distribution for water, vacuum or pressure sewers, water conservation devices used.	100	50-150

Wells and Pumps

Wells penetrating to bedrock or to aquifers in unfrozen materials are probably the most reliable water source. Procedures for well drilling and other installation details are given elsewhere in Alter (1969) and USEPA (1979). In non-permafrost situations, the well casing and any structure above it may require frost-heave protection in the active layer, and the service lines to the building must be thermally protected to avoid freezing. Groundwater sources in the Arctic and sub-Arctic can be expected to be at about 0.5-1.5°C on a year-round basis, so there is little safety margin.

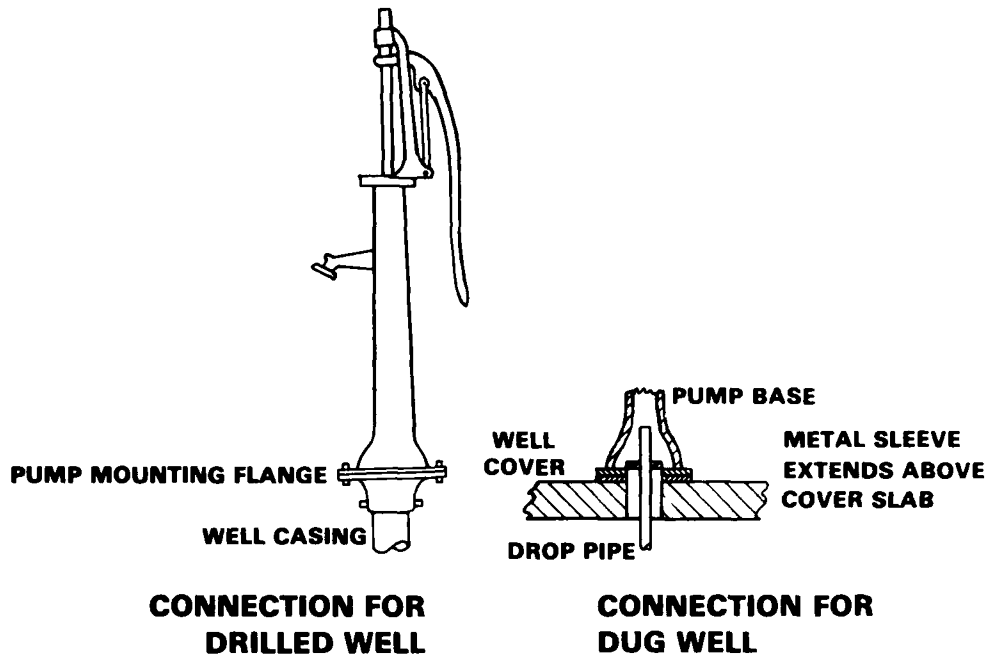


Figure 5. Typical handpump and mounting details for drilled and dug wells.

Wells penetrating the permafrost have another complication since the integrity of surrounding ice-rich permafrost must be maintained, while at the same time preventing the water in the casing from freezing. The complexities involved recommend against the use of subpermafrost wells for individual houses unless absolutely necessary. Pumping of water from a deep well requires electrical power; submersible pumps are most commonly used for this service.

In much of the Arctic the permafrost is 100 m or more thick and the active layer freezes down to the top of the permafrost, so shallow wells are obviously not possible. However, shallow wells can be functional in permanently thawed alluvial material adjacent to existing water bodies or in former stream beds. Heavy-duty hand pumps of the type shown in Figure 5 can function to a depth of about 6 m (at 50 strokes/min, it delivers about 40 L/min). Shallow wells can also be dug by hand or with equipment to depths of about 10 m in most soils. The design features of a typical dug well are illustrated in Figure 6. It is especially important to have a small-diameter "weep" hole in the riser pipe at a location below the frost line. This prevents freezing of water in the riser by allowing it to drain back between pump uses. Driven wells using a slotted well point are also effective for

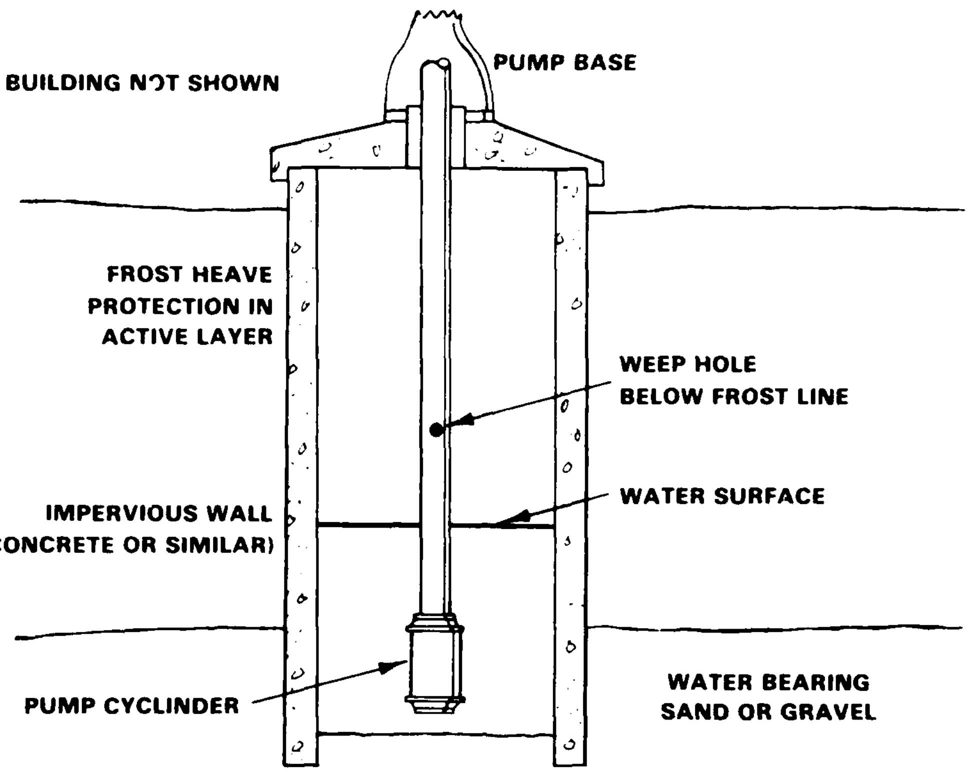


Figure 6. Typical dug well.

shallow wells to about 10-15 m depth. It is necessary to provide thermal protection for the riser of such a well from the ground surface down to the maximum expected depth of frost penetration. An alternative combination is to hand dig or bore through the surface layers and then drive a well point into the water-bearing strata. In either case, the hand pump must be at the well head, so the feasible lift will depend on pump design and the altitude of the site.

The required capacity of the pump will depend on the number of fixtures to be served. Figure 7 can be used to estimate recommended pump capacity for a household, based on the number of fixtures (USEPA 1973). For example, a house with 2 sinks, a toilet, and a shower has four fixtures and should have a pump capacity of at least 0.32 L/s. The lower curve is for interior household uses. If, in addition, some fire protection and/or exterior uses such as gardening or vehicle washing are desired, then the upper curve should be used. These curves are based on the use of conventional fixtures with no water conservation measures employed, so they represent the maximum requirement for cold regions applications.

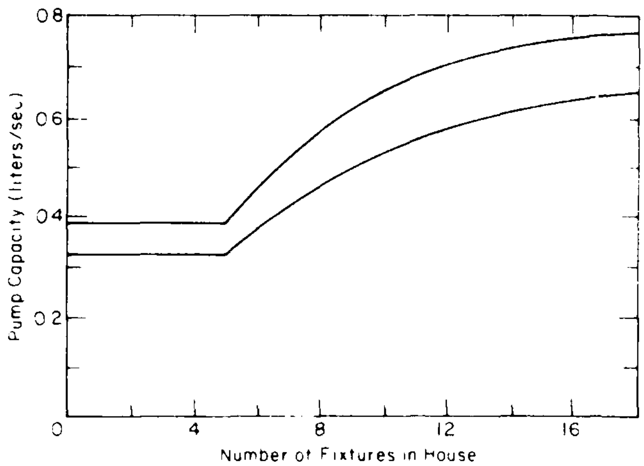


Figure 7. Recommended pump capacity.

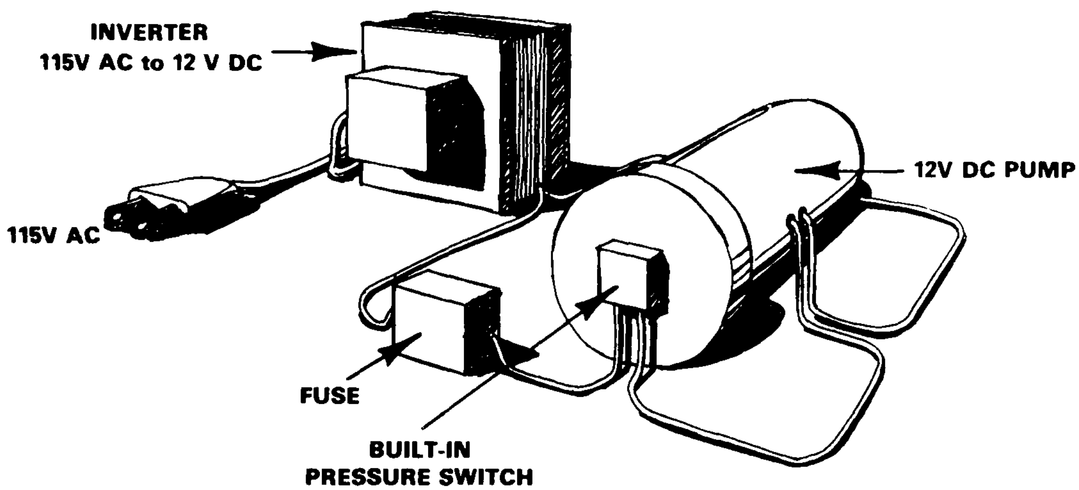


Figure 8. Electrical hookup for small in-house water distribution pump.

In many cases the capacity of a well or spring is less than the values indicated in Figure 7. In those cases the well pump should be compatible with well capacity and deliver the water to in-house storage. The storage must then be large enough to permit in-house pressure distribution at the rate indicated in Figure 7 for conventional services.

Large-capacity, high pressure pumps are not required for in-house distribution from water storage tanks that are on a truck delivery system. Figure 8 illustrates the pump system used in the houses in Galena, Alaska. It is a small-scale 12V d.c. pump of the type that is commonly used in trailers and recreational vehicles. It has an integral pressure switch and automatically turns on in response to demand. It can deliver about 0.2 L/s at 3 m design head. The d.c. pump requires an a.c.-d.c converter for connection to normal a.c. house current. In 1978 the pump cost $32 (U.S.). It should

work reliably for several years and its low cost and ready availability make replacement easy. The pump unit for a conventional house with complete plumbing fixtures would typically combine a 1/4-hp pump with a buffer tank.

Storage Tanks, Plumbing, and Piping

Storage tanks for water and wastewater are essential for houses on a truck delivery system. As indicated previously, water tanks may also be necessary where the on-site water source has a low flow rate. In these cases the storage is sized to meet the daily need, and the low but continuous flow refills the tank during non-use periods.

Buried tanks of concrete or steel or similar materials may be used in unfrozen granular soils. Above-ground or elevated exterior tanks of concrete, steel, wood staves, fabric pillows, or plastic have been used at remote locations, but they are not well-suited for single-family dwellings because of costs and maintenance and aesthetic factors. Ice-rich fine-textured permafrost requires that the tank be constructed above ground for permafrost stability; such a location then requires protection from freezing. The preferred location for both water and sewage tanks is within the building, to take maximum advantage of the thermal protection it offers and to provide easy access for service and maintenance.

Installation within the house imposes certain criteria to ensure maximum efficiency and cost-effectiveness. The most critical is the use of water conservation measures wherever possible. It is not cost-effective (or necessary) to provide a truck delivery system to meet the commonly assumed water use rates (about 10,000 L/week for a family of 4) for conventional facilities in warm climates. At the usage rates shown in Table 2, a storage tank for up to 1-week capacity for 4 persons could range anywhere from 140 to 3600 L.

To reduce pumping requirements, the in-house water tank should be located as high as possible and the wastewater tank as low as possible. Both tanks should be of corrosion-resistant materials and the water tank should not impart tastes or odors to the contents. Plastic materials, particularly fiberglass, offer structural and hygenic advantages.

The technical specifications for the recently (1980) installed water and wastewater storage tanks at Galena, Alaska, included the following provisions:

> 0.5 cm nominal thickness fiberglass, one piece unit, contact mold construction method, 1.3 cm radius of curvature at intersections of tank surfaces; tensile

strength 36,600 N/m^2, flexural strength 40,000 N/m^2, impact strength 61.4 N·m; water tank fabrication with a isophthalic resin during lamination to eliminate taste and odors and a paraffin surfacing wax for a curing agent on all interior surfaces; the wastewater tank will have a resin-rich interior surface for corrosion resistance.

The location of these storage tanks and the related plumbing facilities for the Galena installation are shown in Figures 9, 10, and 11. The 700-L water tank costs about $315 (1978) and the 625-L wastewater tanks about $350 (1978) to fabricate. The water-tank fill line runs to a quick-connect fitting on the house exterior for connection to the hose from the water delivery truck. The pump-out line for the wastewater tank runs to another quick-connnect fitting. As shown in Figures 9 and 11, the wastewater tank is supported by the basic house flooring and is then decked over with plywood. A low-water-use (1 L/flush) toilet is connected directly to the tank. Since the village has public showers and a public laundry, the fixtures in most homes are limited to sinks and the low-water-use toilet, as shown in Figures 10 and 11.

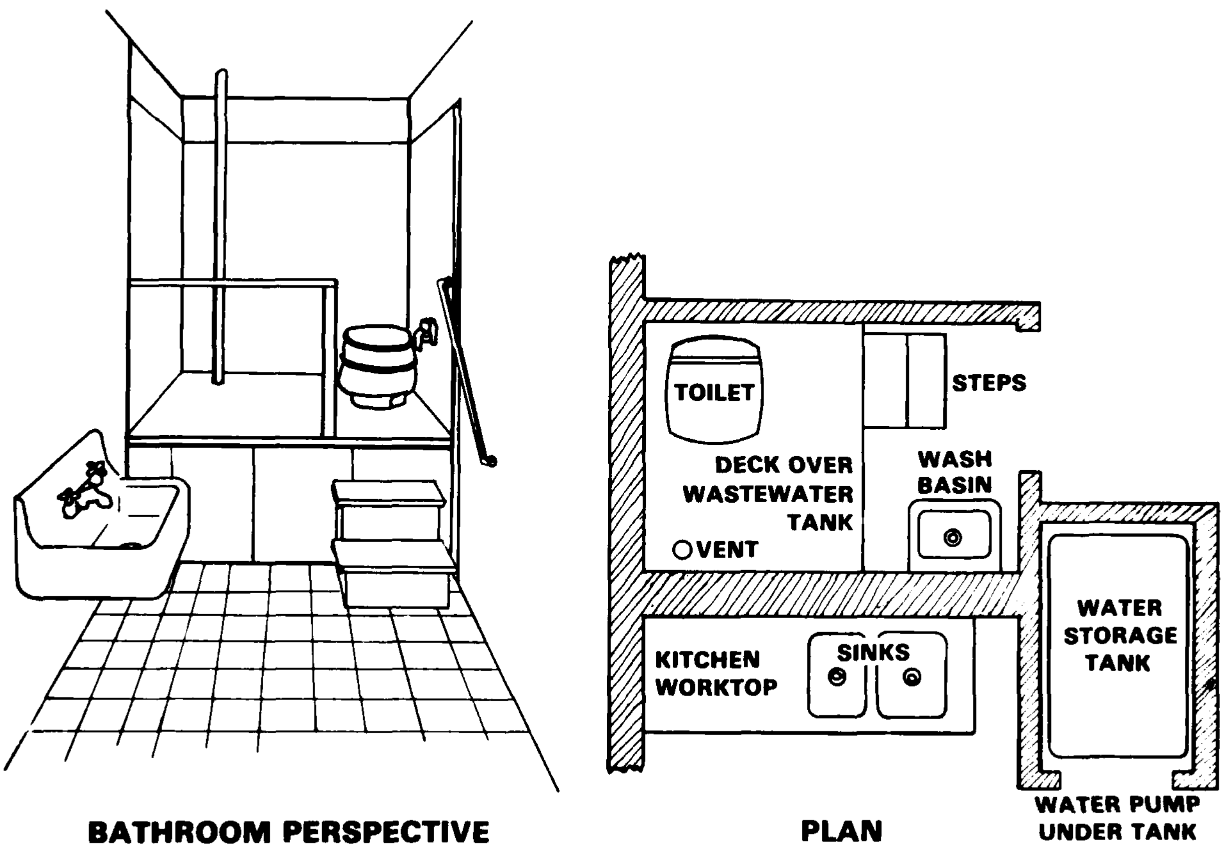


Figure 9. Household facilities for vehicle-hauled water and sewage.

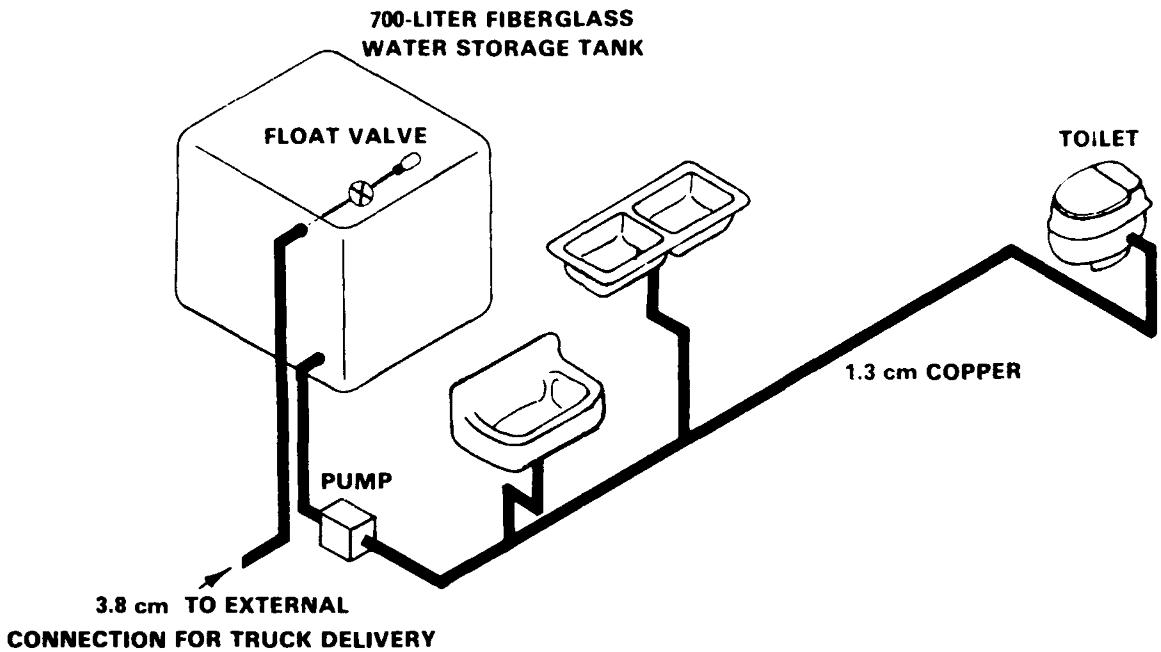


Figure 10. Water supply plumbing for house on truck-hauled water system.

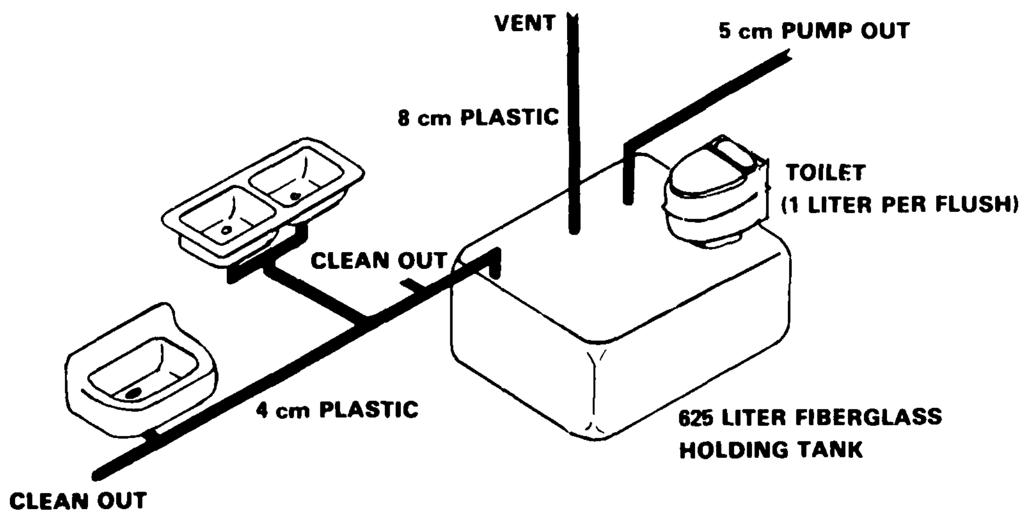


Figure 11. Wastewater plumbing for house on truck-hauled sewage system.

The plumbing details shown in Figures [illegible] are [illegible] regions installations. Copper lines are commonly used for water [illegible] appropriately sized plastic lines with solvent-welded joints [illegible] wastewater. All plumbing should be located along interior walls [illegible] possible for maximum thermal protection. The water lines should [illegible] with drains at the low spots so the system can be emptied during [illegible] periods of power loss and/or no heat in the building. In addition to the normal sink traps, the wastewater lines should have clean-outs at critical locations in the system. Exterior wall penetrations must be done in a way [illegible] protect the integrity of the wall insulation and the vapor barrier. These exterior connections must be dry and empty when not in use. Exterior connections to on-site wells or springs must be insulated and heat-treated or be connected to a circulating type system. Figures 12 and 13 show typical exterior connections for wastewater piping to on-site disposal systems or community sewers.

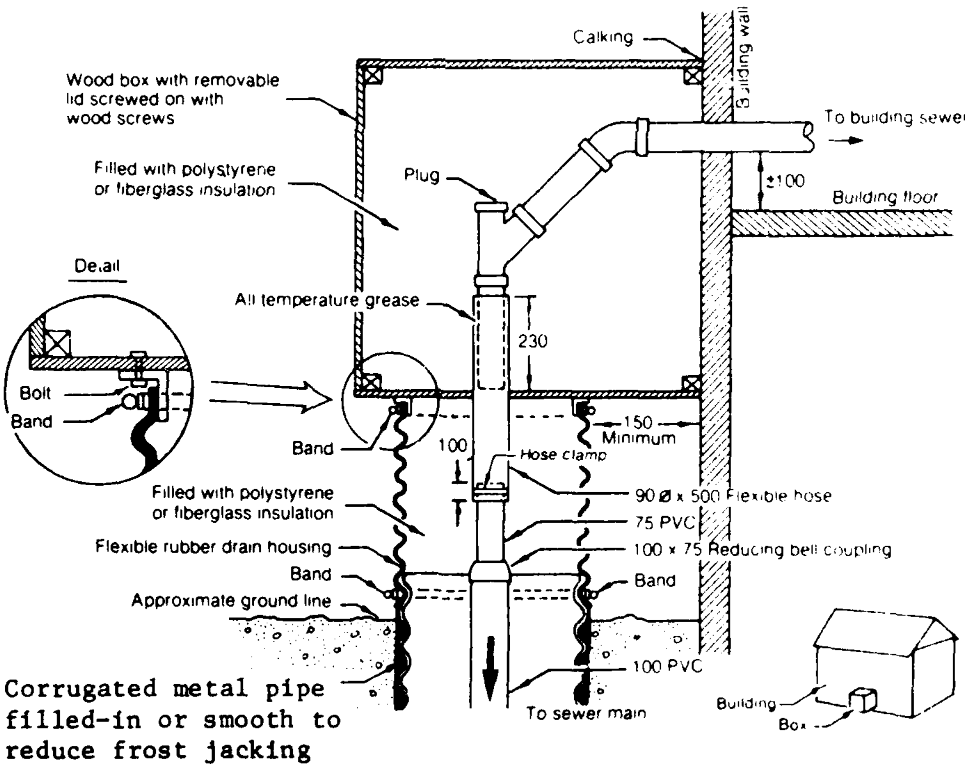


Figure 12. House sewer - wall connection.

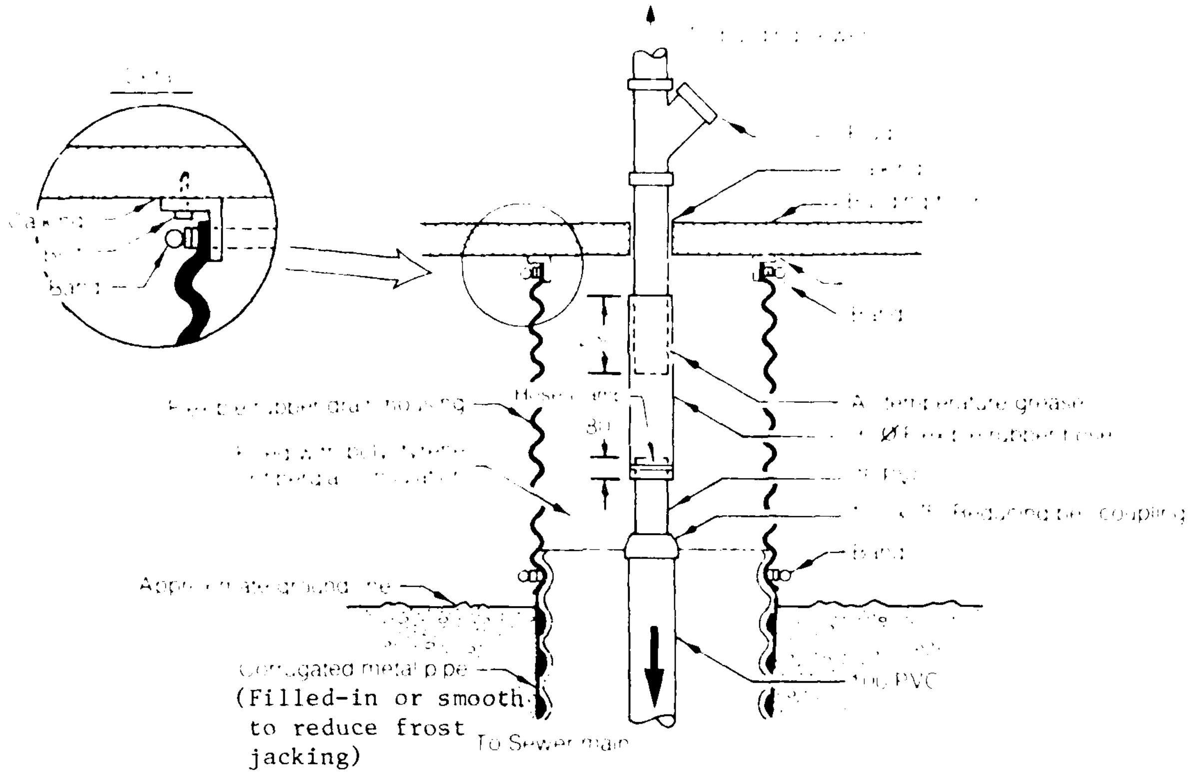


Figure 13. House sewer - floor connection.

The connections and truck hoses used for water and for wastewater should be of different sizes to avoid the risk of cross connections. Both the water and wastewater tanks must be vented to permit air movement during filling or pumping out. Household wastewater tanks are typically 2200 L, but some as large as 4500 L have been used in Canada. It is common practice for the wastewater tank to be up to twice the size of the water storage tank. For the general case, a wastewater tank with a volume at least 400 L greater than the water tank should give adequate service when water conservation measures are used (Gamble and Janssen 1974).

WATER CONSERVATION

Water conservation measures can include simple flow-control orifices in sink and shower pipes to limit flow, automatic spring-loaded return valves on sinks, and a wide variety of low-water-use toilets. The toilet provides the major opportunity for water conservation since conventional units without any modifications will account for about 40% of the typical household water use.

Personal bathing with conventional showers or tub is next and uses about 30% of the water consumed. The balance is used in the laundry (15%), the kitchen (13%), and for miscellaneous purposes (2%) (Cameron and Armstrong 1979).

Toilets

Toilets use more water than any other single fixture within the home. Conventional toilets typically use 20 L/flush, but the reservoir tank can be easily modified to reduce water consumption during flushing. Various modifications are described in Table 3; they range from simple homemade devices, such as weights or plastic bottle inserts, to inexpensive manufactured dams or dual flush attachments. A more expensive modification, applicable to piped systems, replaces the reservoir tank with a small pressure tank.

There are a number of low-water-use toilets available. The lowest use flush tank toilet unit is 3-L model manufactured in Sweden. The lowest use fresh water toilets are the recirculating toilets, which require an initial charge of water and chemicals or other additives. A number of toilet alternatives that do not require any water are also available. These toilets, along with the low-water-use types, are summarized in Table 4. It is important to note that not all of these toilets are applicable or appropriate to a given situation. For example, a mechanical seal toilet must be located directly over a receiving tank, and the 3-L toilet should only discharge into a tank less than 25 m away through a sewer line with a minimum grade of 3%. In addition, various alternatives, including some reuse systems, are beyond the operating capabilities of disinterested, transient individuals.

Bathing

Depending on the habits of the user, a shower will usually use less water than a tub bath, particularly if an inexpensive flow-restricting insert or specially designed low-flow showerhead is installed. Many low-flow showerheads give a satisfactory or even superior shower while saving a considerable volume of water and the energy required to heat it. Other specialty shower units or systems use very little water. Several add-on shower devices are available that will save water, and some increase water convenience, comfort, and safety. Bathing alternatives are summarized in Table 5.

Handheld showers can reduce water consumption by about one half as compared to the conventional fixed shower heads. A very significant savings in household energy use can be achieved by coupling a handheld shower to an in-

Table 3. Toilet modification alternatives.

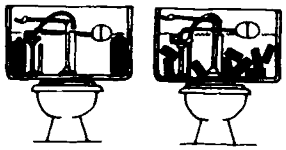
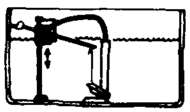
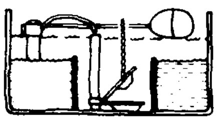
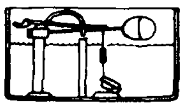
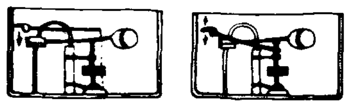
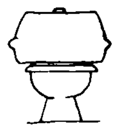
	Principle of operation	Advantages	Disadvantages	Hookups required	Consumption	Approximate cost	
						Capital	Operating
Bricks or plastic bottles 	Bricks or plastic bottles filled with water and weighted with small stones or completely filled with sand or gravel are inserted into the toilet tank. For each flush they displace and, therefore, save water equal to their volume.	Inexpensive, easily installed homemade devices usually consisting of discarded household items. If inadequate flushing results, plastic bottles can be cut reducing the size until the toilet flushes satisfactorily.	Bricks deteriorate in water and particles will clog water jets and lodge under the flush valve causing a continuous leak. They can also crack the tank if dropped or fall over, and multiple bricks will inhibit the flow of water around them. Bricks are not recommended. Plastic bottles can shift and interfere with the flushing mechanism and if filled with sand and not properly sealed, escaping sand can lodge under the flush valve resulting in a continuous leak.	None	[illegible]	[illegible]	None
Improved float assemblies 	Replaces existing conventional float ball and fill valves, allowing water levels to be lowered and adjusted to use exactly the minimum amount of water necessary for efficient flushing.	Improves flushing efficiency and some will facilitate the detection of leaks. Potentially more durable than conventional replacement equipment due to less wear. Valve on leak signaling type is always in fully open or closed position, therefore, is quieter than slow closing conventional ballcocks.	Water savings are essentially limited to the elimination of leaks. Slightly higher cost than conventional replacement equipment.	Connects to [illegible] water line	[illegible]	[illegible]	[illegible]
Dams 	Plastic or metal wall is inserted into toilet tank in a vertical position and sealed against the sides and bottom of tank. Some types encircle the flush valve outlet, but all prevent the lower portion of water from draining out of the tank when the toilet is flushed.	Easy to install and will reduce water usage more than homemade devices. Will not interfere with static head or flush mechanism. Types made of metal and rubber are potentially more durable than those made of plastic.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Weights 	Attached to the ball-chain or rod. After the desired amount of water is flushed the flush handle is released, and the weight immediately forces the stopper back into the flush valve seat, and flow stops.	Nearly as effective as dams in reducing water consumption and can be used in conjunction with dams to maximize savings. Can be homemade.	[illegible]	[illegible]	[illegible]	[illegible]	
Dual-flush mechanisms 	Single action type can be a counter weight, floating cylinder or air bleeder mechanism which manipulates the flush valve stopper. When toilet is flushed normally, only a portion of flush water is released. For a full tank flush, the flush handle is held down. Double action types replace existing flush valve assembly. The flush handle moves in one direction for low volume flush (liquid wastes) and in the opposite direction for full flush (solid wastes).	Allow for [illegible] flush quantities. [illegible] used in conjunction with dams.	[illegible]	[illegible]	[illegible]		
Replacement tanks 	Mounts on existing toilet bowl replacing the whole reservoir tank with a pressure tank cartridge and cover. Water entering the empty tank compresses the air inside, stopping when water and air pressure are equal. When toilet is flushed, compressed air and gravity force water into the bowl.	Uses about half the water used by a conventional toilet tank.	Expensive [illegible]	[illegible]	[illegible]	[illegible]	

Table 4. Toilet alternatives.

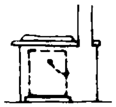
		Principle of operation	Advantages	Disadvantages	Hookups required	Consumption	Approximate cost	
							Capital	Operating
Outhouse		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		
Bucket		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Conventional	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Shallow trap	Same as above, except has a shallower trap and smaller reservoir tank	Same as above, except toilet water use is approximately [illegible] less than conventional	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	European 6L	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	European 3L	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Flush valve		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
Air pressure		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 4 (cont'd).

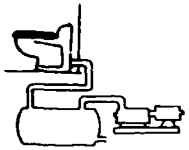
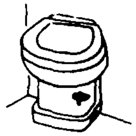
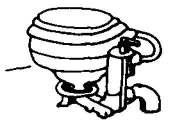
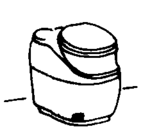
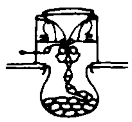
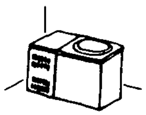
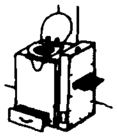
	Principle of operation	Advantages	Disadvantages	Hookups required	Consumption	Approximate cost	
						Capital	Operating
 Vacuum	Vacuum toilet connected to special valve mechanism and discharge piping utilizes an air pressure differential created by partially evacuating the air from the pipe network to transport slugs of wastewater through small diameter piping to central collection vacuum tank.	Uses little water and toilet does not have reservoir tank. Collection system uses small diameter plastic pipe which can be installed relatively independent of grade. Vacuum mains can be laid in same trench as watermains and have less heat loss due to lower volumes of fluid transported. Can be connected to multiple units within the same building or community.	Relatively complex operation and high capital cost. System requires back-up pumps and power. Installation requires qualified personnel.	9.5mm water 38mm waste electricity [illegible]	[illegible]	[illegible]	[illegible]
Mechanical seal 	Pedal or handle opens valve in bottom of bowl and actuates swirl of fresh water to rinse bowl. Also, portable models with detachable holding tank for dumping of waste.	Fresh water flush but very low water use. No chemicals or recirculating. Can be used as portable unit with holding tank.	Sewer lines will clog due to low volume flush, therefore should only be used when there is a relatively straight drop into a holding tank. Portable unit must be dumped and recharged.	Varies from none to 9.5 mm water and 75 mm waste to holding tank	[illegible] litres/flush	[illegible]	[illegible]
Marine 	Hand or electric pump brings water into bowl. Valve is turned, same pump ejects wastes. Can pump wastes uphill.	Relatively low water usage. Can pump its waste uphill. Pumps its own water and could be used as a recirculating toilet.	Clogs relatively easily. Relatively complicated to use. Power consumption for electric models.	19 mm water 38 mm waste 120V or 12V for electric models	[illegible]	[illegible]	[illegible]
Recirculating 	Hand and/or electric pump swirls filtered, chemically treated wastewater from holding chamber to flush and rinse bowl. When full, unit must be dumped and recharged with chemical and water. Portable or fixed models available.	Uses very little water. Fixed units can be used with conventional plumbing, usually [illegible] charge to holding tank	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Packaging 	Wastes drop into plastic lined bowl. The continuous tube of plastic is drawn down through the bowl and is heat sealed to form a series of "sausages." Plastic bag under toilet collects "sausages" which must be periodically removed.	Handling of waste is improved. Odors and breakage of bags is minimized by isolating small quantities of waste in separate "sausages."	[illegible]	[illegible]	[illegible]		[illegible]
Freezing 	Wastes drop into plastic bag in a small freezing compartment. When full, bag is removed for pick-up and replaced with new bag.	Freezing prevents decomposition, odors and handling of waste is much easier and more sanitary and acceptable.	Relatively expensive to buy, requires [illegible] bags, and electricity. Power failure or defrosting reactivates decomposition. Collection and ultimate disposal of bags must be organized and can create problems.	[illegible]	[illegible]	[illegible]	[illegible]
Incinerating 	Wastes are incinerated in timed cycle after each use. Ash must be removed periodically. Models use electricity or gas.	No liquid waste generated and very little ash to dispose of. Reduces pollution.	Uses considerable energy. Some models require use of paper bowl liner with each use. Relatively complex mechanism. Must be vented.	[illegible]	[illegible]	[illegible]	[illegible]

Table 4 (cont'd).

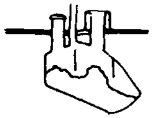
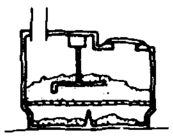
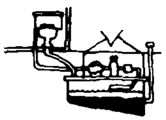
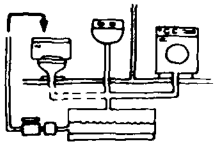
		Principle of operation	Advantages	Disadvantages	Hookups required	Consumption	Approximate cost	
							Capital	Operating
Composting (large)		Kitchen garbage and human wastes are digested by microorganisms, producing fertilizer.	End product, compost, can be used as fertilizer. Reduces pollution. No water, sewer or electrical hookups required. No moving parts. Little maintenance.	High initial cost for unit and installation. Unit is very large, requiring considerable basement space.	[illegible] vent	None	[illegible]	[illegible]
Composting (small)		Same as above, except compact and uses forced air circulation and heat to speed process.	No water or sewer hookups required. Unit is relatively small and can be installed in conventional washroom. End product, compost, can be used as fertilizer. Reduces pollution.	Expensive to buy and relatively complex to maintain and operate properly. Requires significant energy input and can not handle shock loading of organic and liquid wastes.	120V electricity; 100 mm vent	Electricity, no water	[illegible]	[illegible]
Synthetic fluid		System utilizes special chemical fluid or mineral oil as flushing medium. Waste materials settle out in holding tank and fluid is filtered and recycled to conventional toilet. Waste must be pumped out about once a year.	Utilizes conventional toilet and plumbing but no water. Can be used in conjunction with an incinerator to destroy concentrated wastes. Applicable for multiple units such as camps or public washrooms.	High initial cost for unit and installation. Requires significant space and is relatively complex. Requires replacement of lost fluid and addition of odor control chemicals. Energy requirement for pumps and incinerator, if used, otherwise waste must be pumped out for disposal.	[illegible] recycle system; [illegible] mm water; [illegible] mm waste; Electricity for recycle system	Electricity, no water	[illegible]	[illegible]
Treatment systems (recycle)		Recycle of treated and filtered toilet and/or other wastewater for toilet flushing. Sludge in tank must be pumped out every year or two.	Uses little or no fresh water. Some will accept wastewater from other fixtures.	High maintenance and capital cost. Requires filters, disinfectant, dye, pumps and electrical power.	[illegible] treatment recycle system; [illegible] mm water; [illegible] mm waste; electricity for treatment and recycle system	[illegible]	[illegible]	[illegible]
Urinals		Handle releases high velocity water injection siphoning liquid wastes through a trap.	Low volume flush models use very little water compared to conventional toilet. Uses conventional plumbing. Commonly used in public washrooms.	Relatively expensive addition to household washroom. Only handles liquid waste. Low consumer acceptance due to institutional and public image.	[illegible] mm water; [illegible] mm waste	[illegible]		[illegible]

Table 5. Bathing alternatives.

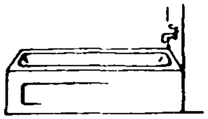
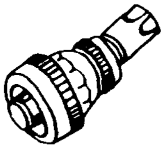
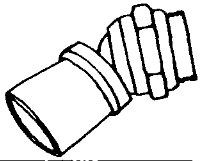
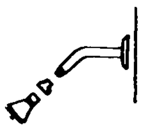
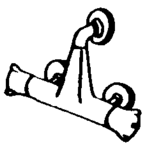
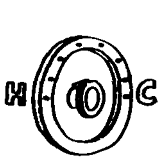
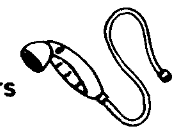
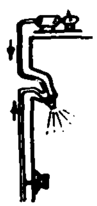
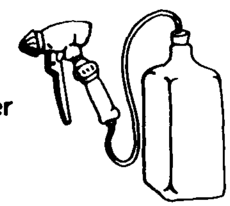
	Principle of operation	Advantages	Disadvantages	Hookups required	Consumption	Approximate cost	
						Capital	Operating
Bathtubs 	Vitreous china, fiberglass, or metal bathtub is filled with mixture of hot and cold water for bathing.	Facilitates personal hygiene and relaxation. Can be used without plumbing system and water can be reused. Level to which tub is filled need not be excessive, and water use is independent of duration of bath. Water can be left in tub to recover heat before discharge.	[illegible] relatively fixed volume of water per use. Large bathtubs with or without whirlpool spas, use large volumes of water. Most are not designed to conform to the shape of human body or insulated to reduce heat loss.	Varies from none to 9.5 mm H&C water and 38 mm waste	Varies with size of tub and user habits. Approx. 150 litres/use	Galvanized $30-$50 Vitreous china & fiberglass $80-[illegible]	Depends on cost of water and energy for hot water heating.
Conventional shower heads 	Blend of hot and cold water flows through a fitting with small openings to produce a water spray.	Convenient, quick method of body cleansing and rinsing. Water use can be regulated by time spent in shower.	Requires water and sewer plumbing and shower stall. Water consumption is high particularly with "massaging" type showerheads. Flow restrictors installed on some models may reduce the quality of shower to unfavorable as may low pressure systems.	9.5 mm H&C water and 38 mm waste	15-40 lpm Typically 25 lpm "massaging" as high as 55 lpm Normal shower duration is 5 mins.	Normal $5-$25 Typically $8 massaging $20-$50	Depends on costs. 5 minute shower every second day for family of four would use about [illegible] litres per day, ½ hot water.
Low flow shower heads 	Same as above, except water flow is restricted. Aerating types mix air with the water.	Same as above, except uses less water and energy to heat hot water for the same amount of time spent showering without sacrificing shower quality. Aerating types use less water. Most work well on low pressure systems by delivering a constant water flow regardless of pressure changes.	Generally a little more expensive than conventional shower heads and spray pattern is often narrower. Low flow may be noticeable by some, particularly for washing hair. Aerating type have non adjustable sprays.	Same as above	[illegible]-12 lpm Typically 9 lpm	$[illegible]-$25 Typically $10	Same as above, except family of four would use about 90 litres per day, ½ hot water.
Flow controls 	Small diameter orifice which restricts the flow of water. They are either an insert that slips into the shower water supply line or an independent fitting that is coupled onto the supply line ahead of the shower head.	Inexpensive retrofit method of reducing the flow of conventional shower heads. Can be homemade, consisting of a rubber washer with small diameter opening.	May reduce shower quality of some conventional showerheads.	Attaches, threads or inserts ahead of shower head	8-[illegible] lpm Typically [illegible] lpm	[illegible]	Same as conventional, except consumption would be reduced to about 100 litres per day, ½ hot water.
Shut-off valves 	A valve installed between the shower arm and the shower head to allow turning off of the water at the shower head without adjusting other controls. Some shower heads have shut-off valve built in.	Saves water by allowing user to conveniently shut off water at the showerhead while not under spray, lathering up, washing hair, etc. Some types have a small water flow while in off position which maintains the selected water temperature.	Water temperatures in riser stem or supply lines may change while valve is turned off. User may feel chilled when shower spray is turned off.	Attaches ahead of shower head	Varies with flow rate and user habits.	[illegible]	Depends on flow rate and user habits. Approx. [illegible] savings.
Thermostatic mixing valves 	Controls temperature changes from the hot and cold water supply lines by means of sensitive bi-metal spring. Two metals expand at different rates causing spring to move interior mechanism which controls the hot and cold supply lines, thus, maintaining a constant ratio of hot and cold water. Has two control knobs; one for temperature selection and the other controls the rate of water flow.	Provides constant pre-selected water temperature regardless of flow (pressure) or temperature changes in hot or cold supply lines. Increases user convenience, comfort and safety by reacting quickly to supply line temperature changes. One valve can control both shower and bath and/or other outlets.	Costs two to three times the price of conventional valves.	9.5 mm H&C water and supply line to shower head	Not applicable, reduces waste	Approx. [illegible]	None
Pressure balancing mixing valves 	Designed specifically for showers, it compensates instantly for pressure changes in either the hot or cold water supply lines, usually due to the use of other fixtures, thus, maintaining the selected flow mixture resulting in a consistent shower temperature.	Avoids discomfort and wasting of water by maintaining a consistent shower temperature.	Does not compensate for temperature changes from source unless accompanied by a pressure change. Costs about twice as much as conventional valves.	9.5 mm H&C water and supply line to showerhead	Not applicable, reduces waste	Approx. [illegible]	None

Table 5 (cont'd).

	Principle of operation	Advantages	Disadvantages	Hookups required	Consumption	Approximate cost	
						Capital	Operating
Hand held showers 	Shower head type fitting attached to a short hose, for hand held use. Can be permanently attached for use in shower stall or connected to end of faucet on sink basin.	Increases ability to get the water spray where it is desired with a minimum of inconvenience. Available with built in flow control and on-off valve. Can be permanently clipped to wall or attached to any faucet. Can be used to compliment conventional or low flow shower head, particularly for washing hair.	Potential danger of contamination by back-syphonage. If not clipped to wall, requires use of one hand. The wetting and rinsing operation may be inconvenient to some.	Faucet or shower outlet and 38 mm waste.	5-30 Lpm greater for massage type.	$10-$30	Depends on costs and user habits. As low as 10 [illegible] shower
 Air assisted shower system	A small centrifugal air blower supplies *air to a special showerhead where air and* water are mixed to create a fine spray.	Very low water consumption while maintaining satisfactory cleansing. Can use in-line heater, therefore, no need for hot water supply line. Main economic advantage is amount of energy saved in water heating.	High capital and installation cost. Due to length of time required to drain water in hot water supply line, in-line heater, circulation of hot water or short distance to hot water tank is necessary. Requires enclosed shower stall. Separate blower required for each shower head. Unsatisfactory shower for some.	9.5 mm H&C water 38 mm waste 120V electrical for blower.	2 lpm	[illegible]	Depends on costs, family of four would use about [illegible] litres per day, [illegible] water [illegible] per year for [illegible]
Atomizer shower 	Water of the desired temperature is delivered to an atomizing nozzle *which produces a very fine spray* (mist). The atomized water spray removes surface cells, dirt and soap.	Uses extremely little water. Existing designs are self contained and require no water, sewer or power hookups and are portable.	Takes a long time to have a "complete shower." Drifting of spray if not within an enclosure. May require additional system for washing hair. Technology and plumbing not fully developed for conventional houses. Un-satisfactory shower for many.	None for self contained models.	As low as 1 [illegible] shower	Approx. $5-$10	Negligible

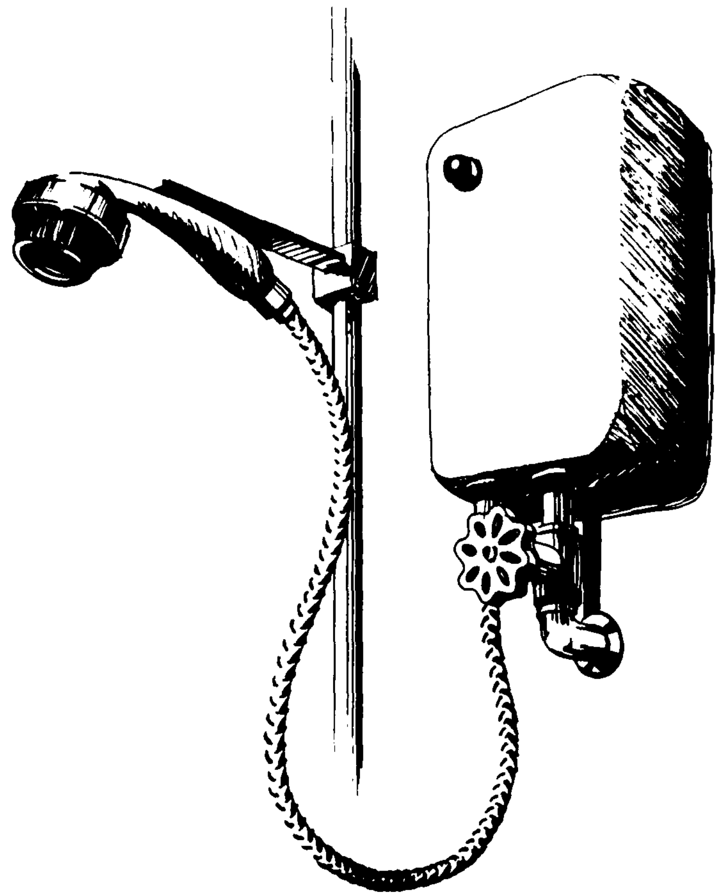


Figure 14. Typical instant water heater and shower fixture.

stant on-line water heater as shown in Figure 14. The energy savings is achieved by eliminating the conventional hot water tank. The unit is thermostatically controlled and instantaneously heats the water flowing through it. Both electrical and gas-fired units are commercially available. The gas fired units claim at least a 25% fuel savings as compared to a conventional hot-water tank system. Single heating units can be located in the house at each point of hot water use, or a larger heater unit can be located at a central point. In 1980, the electrical shower unit shown in Figure 14 cost about $120 (U.S.) at the source.

Laundry

Hand laundering has the potential of using the least amount of water, but considerable user time and effort is required. Wringer washers are versatile and the water is easily reused, but they have been largely superceded by the more convenient automatic washing machines. Numerous top-loading

automatic washers are available, some of which use considerably less water than others. The more efficient tumble action of the front-load washer makes it the lowest hot water and total water user of the automatic washers. They are, however, slightly more expensive. Laundry alternatives are summarized in Table 6.

Kitchen

In the kitchen, dishwashing uses the most water. Hand-washing can be done with very little water but may entail some inconvenience and extra effort. If an automatic dishwasher is always loaded to capacity for each full cycle of operation, its water use will be comparable to hand-washing in a filled sink and rinsing under a free-flowing stream of water. In-sink food waste disposal units are a modern convenience that, if judiciously used, will not significantly increase household water use. Other kitchen operations, such as drinking and cooking, use relatively fixed and small volumes of water. The wasting of water can be reduced by adjusting water habits, such as keeping a container of cold water in the refrigerator. There are also a number of faucet attachments that reduce the amount of water flow and waste compared to conventional faucets. Water-flow reduction at faucets has the added benefit of energy savings, since approximately 50%-75% of the flow is heated water. Faucets and faucet attachments are summarized under miscellaneous water use alternatives in Table 7.

Household systems are also discussed in Table 7. All of these alternatives involve some alteration of conventional household plumbing, and provide water and energy savings.

Economics

There are practical and technical limitations to the comparison and selection of economical water conservation alternatives for an individual building. All capital and O&M costs associated with an alternative must be discounted to obtain its present worth. Since these depend upon the unit costs for water, sewerage, and energy, the number of uses, the volume used, and O&M costs, each new and retrofit situation will be different.

Despite these difficulties some general recommendations can be made. For piped systems, there is no need for toilets to use over 15 L/flush. Low-flow showers and flow-control aerators are almost universally economical. For truck delivery systems, more restrictive alternatives are often necessary; mechanical flush toilets should be used wherever possible. Where the

Table 6. Laundry alternatives.

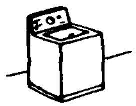
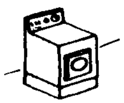
	Principle of operation	Advantages	Disadvantages	Hookups required	Consumption	Approximate cost	
						Capital	Operating
Hand laundering 	Beating or rubbing of articles together or rubbing on scrub-board in water filled tub or basin. Manual wringing of articles to remove excess water.	Complete user control over water quantity and temperature and number of article laundered in same wash or rinse water. Does not require electrical hook-up or household plumbing.	Highly labor intensive requiring considerable time, inconvenience and effort. Water use depends on size of tub and user habits.	None	Depends upon user	Low to none	None
Wringer washer 	Agitator washing motion in user filled tub. User activates pump to drain wash or rinse water from tub. Laundered articles are manually fed through wringer to remove excess water.	User control over water quantity and temperature and number of wash loads laundered in same wash or rinse water. Can be moved to convenient storage location.	Capacity of tub varies with manufacturer. Requires time but not nearly as inconvenient or labor intensive as hand laundering. Possible to overfill or use too much water for varying wash load sizes. Wringer can be hazardous. Requires electrical hookup and storage space.	120V electrical and should be close to water supply and sewer drain.	Varies according to size of tub, manufacturers recommendations and number of reuses of wash and rinse water. Usually less than automatic washers	$200 $500	Depends on cost of water and power. Household of 4 would wash an average of 5 loads per week
Top loading automatic washer 	Top loading agitator motion for preselected wash/rinse/spin cycles. Wash and rinse water is automatically filled and drained with excess water spun from laundered articles.	Convenient automatic wash and spin dry cycles are labor saving. Other convenience features allow for water level and temperature selection Some models offer a suds-saver attachment which will save water.	High range of water use among currently available models. Water level selection not possible on some models. Minimum wash load size may be high for small families. Temperature selection does not allow cold water rinsing on some models. Requires electrical and plumbing hookup and permanent space.	120V electrical and must be connected to water supply and sewer drain	Total water use 140 260 litres Hot water only 40 87 litres	$350 $700 average $500	Same as above
Low water use top loading automatic washer	Same as above.	Same as above except uses less water per cycle, promoting less use of detergents and other laundry additives.	Has slightly higher cost than average of other top load models. Maximum wash load sizes may be low for some families. Requires electrical and plumbing hookup and permanent space	Same as above	Total water use 131 146 litres Hot water only 27 53 litres	$575	Requires less water and laundry additives than above
Front loading automatic washer 	Front-loading tumble wash motion for preselected wash/rinse/spin cycles. Wash and rinse water is automatically filled and drained with excess water spun from laundered articles.	Lowest water use of currently available automatic washers Has water level and temperature selection convenience features. Uses less detergent and other laundry additives and requires less operational energy than average of top load models.	Front loading door is not preferred by many consumers. Has slightly higher cost than average of top loading models. Maximum wash load size may be low for large families. Requires electrical and plumbing hookup and permanent space.	Same as above	Total water use 119 litres Hot water only 20 40 litres	$650	Requires less water, operating power and laundry additives than above

Table 7. Miscellaneous water conservation alternatives.

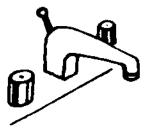
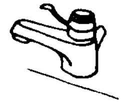
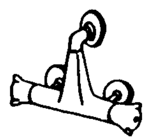
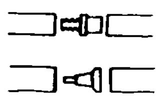
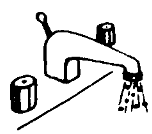
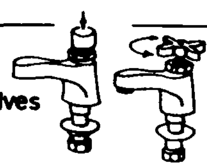
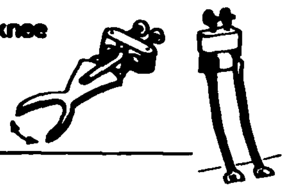
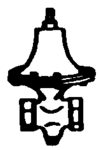
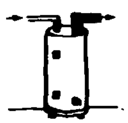
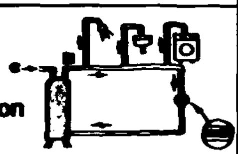
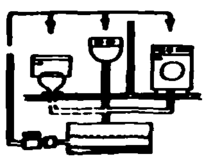
	Principle of operation	Advantages	Disadvantages	Hookups required	Consumption	Approximate cost	
						Capital	Operating
Conventional faucets 	Water flow from supply line is controlled by rubber gasket which is turned down onto a seat. Gasket is connected to valve stem and operated by a handgrip. Available with single spigot or separate hot and cold faucets.	Valve controls water flow rate. Washerless valves with ceramic discs instead of rubber resist water and mechanical wear and operating temperatures up to 80°C.	High unrestricted flow rates. Wearing of rubber gasket type results in water loss due to leakage.	H&C water supply lines	20 - 50 Lpm	$15 - $40 Washerless $30 - $50	Depends on cost of water and hot water heating
Mixing faucets 	Single faucet with one control handle that is used to adjust both flow rate and temperature of water.	Desired flow and temperature can be quickly selected and adjusted with only one hand, thereby reducing waste. Compact.	More expensive than conventional.	Same as above	Reduces waste	$30 - $50	Same as above
Spray faucets 	Single faucet which delivers water in a spray, much like a shower head. Flow rate is preset and control knob is used for on/off operation and temperature selection.	Minimum pressure requirement of 13 kPa ideal for gravity tank systems. Compact and can use small diameter water supply and drain lines. Possible to use an in-line water heater eliminating need for hot water line.	Inconvenient for filling containers due to very low flow rate. Institutional image as they are commonly installed in public restrooms. Cost slightly more than comparable conventional faucets.	Same as above	2 - 3.5 Lpm	$45	Same as above
Thermostatic mixing valves 	Temperature changes from the hot and cold water supply lines are controlled by means of sensitive bi-metal spring. Two metals expand at different rates causing spring to move interior mechanism which controls the hot and cold supply lines, thus, maintaining a constant ratio of hot and cold water. Has two control knobs; one for temperature selection and the other controls the rate of water flow.	Provides constant pre-selected water temperature irregardless of flow (pressure) or temperature changes in hot or cold supply lines. Increases user convenience, comfort and safety by reacting quickly to supply line temperature changes. One valve can control multiple water fixtures.	Expensive and generally used to supplement other faucets.	9.5mm H&C water and supply line to faucet.	Savings are up to 40% of that used by conventional faucets.	Approx. $70	None
Flow controls 	Reduce water flow rate by means of small diameter orifice in the supply lines ahead of fixtures or on end of spigot. Are either an insert or a threaded fitting. Most will compensate for pressure changes in water supply line to produce a constant flow rate.	Reduces flow rate where they are higher than desired or needed. Inexpensive and usually easily installed as retrofit. Some faucets have them built in. Available with various maximum flow rates.	May require cutting of existing water lines to install in-line type. Some users may feel flow rate is too low. Takes longer to fill and no water savings when filling containers such as a glass or bathtub	Threads or inserts into supply line	8 - 12 Lpm Typically 10 Lpm	$1 - $6	None
Aerators 	Attaches to end of spigot and gives appearance of larger flow than actually present by breaking up flow and introducing air bubbles into the stream of water.	Restricts flow a little, however, main advantage is water use is reduced due to illusion of larger flow. Aerated flow feels gentle and greatly reduces splashing. New faucets generally equipped with an aerator but are inexpensive and easily installed on end of spigot of existing faucets. Some aerators have built in flow control increasing water conservation.	May not fit all old style faucets without an adaptor. Reduces flow rate slightly	Threads onto end of faucet	10 - 25 Lpm	$1 - $5	None
Self closing valves 	Spring loaded valve type, simply shuts off water supply immediately upon release. Timer valves are usually a single faucet with preset flow rate and temperature which automatically close due to accumulated water pressure.	Reduces waste since on only for time actually needed and ensures it will not be left on unattended or after use. Can be used with thermostatic mixing valve.	Do not operate unattended and therefore generally not practical for households. Separate spring loaded hot and cold faucets are inconvenient and warm water can only be obtained by mixing in bowl or container. Do not have temperature or flow rate selection.	H&C water - only lines	Reduces waste	$30 - $40	Depends on cost of water and hot water heating

Table 7 (cont'd).

	Principle of operation	Advantages	Disadvantages	Hookups required	Consumption	Approximate cost: Capital	Approximate cost: Operating
Foot or knee valves 	Faucet valve is activated by depressing a foot or knee lever and when released automatically returns to off position.	Reduces waste since water is on only when activated. Does not require hands to operate, therefore is convenient and sanitary.	Initial cost and modifications to existing equipment is expensive. Some do not allow temperature or flow rate selection. Must be attended to operate.	Mounting on floor or cabinet and controls to H&C water supply lines.	Reduces waste	\$75 - \$120	None
 Pressure regulator	Adjustable spring is used to change pressure on a rubber diaphragm which in turn maintains the building water pressure at a preset value below the water main pressure.	Used where excessive water main pressures could burst fittings or cause excessive noise, vibration and leakage. Reduces water use and waste since maximum flow rate is reduced. Provides constant water pressure to building.	Lower pressure and therefore flow rate will increase time to obtain fixed volume of water.	Connects to building water supply line.	Saves water in all water outlets.	\$30	None
Water pipe insulation 	Insulation is placed or wrapped around water lines, usually hot water only, to reduce heat loss and help maintain temperature level of water in pipes.	Reduces heat loss and rate of cooling of water in pipes thus reducing wasting of water left standing in lines.	May be difficult, expensive and/or impractical to add to some existing water systems.	None	Approx. savings of 7.5 L/person·d	\$1.50 - \$3 per meter	None
Water circulation 	Water pipes in the building or particular area are looped back to hot water tank and a small pump circulates water within the loop. Buildings with individual water systems only need a return line from each faucet to the cistern and a valve to allow draining. Faucets or other water outlets tap off of the loop. Usually only done for hot water pipes.	Eliminates need to waste cooled water standing in line between the heater and faucet before hot water is available. Provides hot water instantly since supply loop is maintained at hot water heater temperature. Circulation pump can be put on timer or thermostatic control to reduce heat loss and pump operating time.	Retrofitting existing systems may be impractical. Increased heat loss particularly for un-insulated pipes and where circulation pump is not on a timer. Circulation of water requires a pump.	Circulation pump (electricity) and return piping.	Reduces waste	\$100 pump \$25 plumbing	Nominal power for pump.
Recycle systems 	Household wastewater is collected and treated for reuse. Some systems only recycle greywater and may not recycle for drinking and cooking purposes. Treatment methods may include biological, chemical precipitation, filtration, carbon adsorption, reverse osmosis, distillation, disinfection and/or others.	Reduces total water requirements to zero or minimal. Building can be independent of water and sewer systems.	Very high capital and operating cost. Complex and high technology beyond most householders capabilities to maintain. Recycle of wastewater, except for toilet flushing, is a health hazard and is not aesthetically acceptable by many. Requires energy, chemicals and scheduled servicing by qualified personnel. Takes up space and may require alternative system for emergencies.	Electrical for treatment system and pumps, recycle piping and standby system.	Depends on system.	\$2500 - \$5000	Cost of chemicals and power requirement. Cost of recommended monthly servicing. Cost for fresh and makeup water.

sewage holding tank cannot be located directly below the toilet, a recirculating toilet is usually the most economical, despite the costs of chemicals. Toilets that use more than 6 L/flush should not be installed. Low-flow showers, hand-held showers, flow-control aerators, and mixing faucets will be economical. Front-load laundry machines will be economical for new installations and high water users.

Where utility costs are very high and/or water supply is limited, even more severe steps are necessary. Even nongravity piped sewer systems do not allow the control over water use that is inherent in trucked systems and central facilities. In addition to the trucked system recommendations above, devices such as spray and self-closing faucets, specialty shower systems, and timers on showers can be used. Water conservation is usually more economical than grey-water reuse. This alternative should only be considered for central facilities and where other considerations such as zero pollution are paramount. Reuse must be approached with caution due to the complex treatment systems and controls that are necessary.

Grey-Water/Black-Water Systems

The separation of grey water (from sinks, baths, and laundries) from black water (from toilets) is often described as a water conservation technique. The degree of conservation achieved actually depends on the type of fixtures used and not on the concept itself. The separation of gray and black water may offer some advantages for treatment and/or disposal, but in many cases the two flow streams are recombined for final disposal. The ultimate possibility is to eliminate the black-water flow altogether by using a non-water carriage unit, such as a composting or incinerating toilet or a simple bucket and bag toilet.

Composting toilets are described in Table 4. They have a potential advantage in that they will accept kitchen garbage in addition to human wastes, which lessens the solid waste disposal problem. The large units require no power, so there is no cost for operation, but they do require a very large space that has to be directly underneath the disposal points (toilet and kitchen). The smaller units have electric or gas heating sources for more rapid evaporation of liquids. Composting toilets function properly when maintained, but they are best suited where there has been a voluntary commitment on the part of the occupant to install and then to maintain them. They are less well suited to rental or institutional housing where the occupants may not have a personal commitment to the successful operation of the unit.

Bucket toilets and "honey bags" are still in use in many villages and isolated locations in cold regions because more modern concepts are too expensive. In the past, the collection and disposal of the honey bags has sometimes been considered a solid-waste management problem, but honey bags should not be handled as a solid waste on an individual or a community basis and disposed of in open dumps. They are unsanitary human wastes and should be disposed of accordingly.

WASTEWATER MANAGEMENT

Community systems (pipes, truck hauling) are not always possible or economical so it is often necessary to provide for on-site wastewater treatment and disposal. Community treatment systems are designed to meet regulatory requirements for the protection of public health and the environment at the discharge point. By contrast, on-site treatment systems are generally designed to permit optimum operation of the final disposal step (i.e. septic tank to avoid clogging the leach field). Exceptions are discharges to regulated streams and treatment to allow some level of reuse of the wastewater. A wide variety of concepts and proprietary equipment are available for these small scale, on-site requirements (Rice 1975, State of California 1977, USEPA 1980, Bauer et al. 1981).

Direct Disposal

The pit privy is one of the earliest and is still just about the only method for direct on-site disposal of human wastes without some type of preliminary treatment. Figure 15 illustrates W. Ryan's design for a pit privy in common use in Alaska. It can be constructed on site from standard lumber, plywood, and other materials. The privy structure is mounted on simple skids so it can be easily moved to a new pit when the time comes. The step and entrance deck are also portable. The entrance deck and privy floor are elevated above the ground surface to keep the doorway above accumulated winter snow and easily accessible. The pit should be about 1 m in diameter and as deep as it is possible to excavate. The privy structure is located over the completed hole, and any remaining open areas are covered with boards and plastic and a layer of soil backfill. There is a vent, as shown in Figure 15, but additional odor control is possible with periodic layers of ashes or lime. A pit 1 m in diameter and about 2.5 m deep might last a family of 4 from 2 to 3 years if it is just used for human wastes. The replacement pit

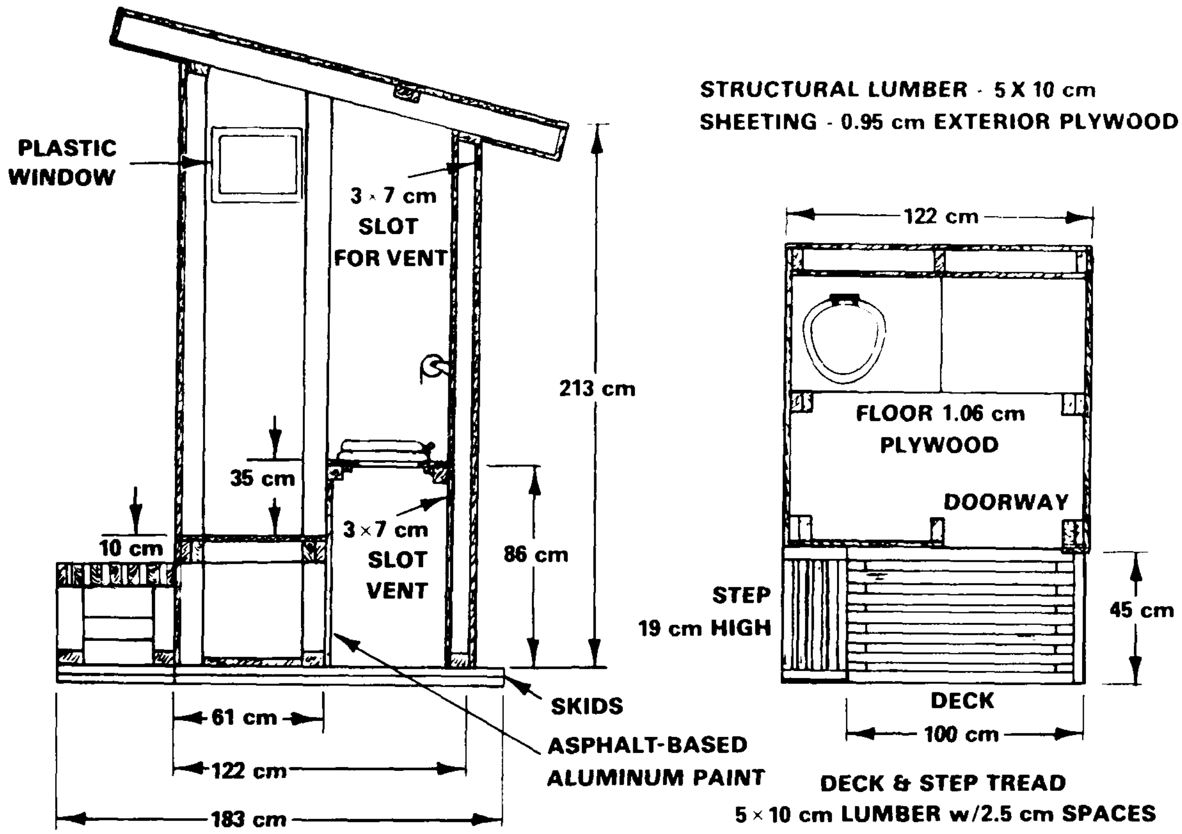


Figure 15. Ryan's Alaska privy.

should be at least 2-4 m away from the original hole to ensure soil stability and to prevent infiltration from the old hole to the new one.

Vault toilets are similar in concept to the privy, but they are usually of more permanent construction materials at a permanent location. They are not common for single-family dwellings but are extensively used for on-site sanitation at parks and playgrounds and similar remote recreational facilities (Cook 1978). Figure 16 illustrates the design of a typical vault toilet construction. The figure does not show the enclosing building, and a single vault can serve more than the one toilet unit shown. The use of four vertical pit walls and a separate liner is usually cheaper and easier than attempting to construct a completely watertight structure on site. Both reinforced Hypalon and the more rigid cross-linked polyethylene have been successfully used as liners (Cook 1978). If the thinner and more flexible Hypalon is used, a thin layer of concrete should be placed on the bottom for protection during the cleaning operations. The vault should have a maximum capacity of about 1900 L unless the design analysis shows that larger capac-

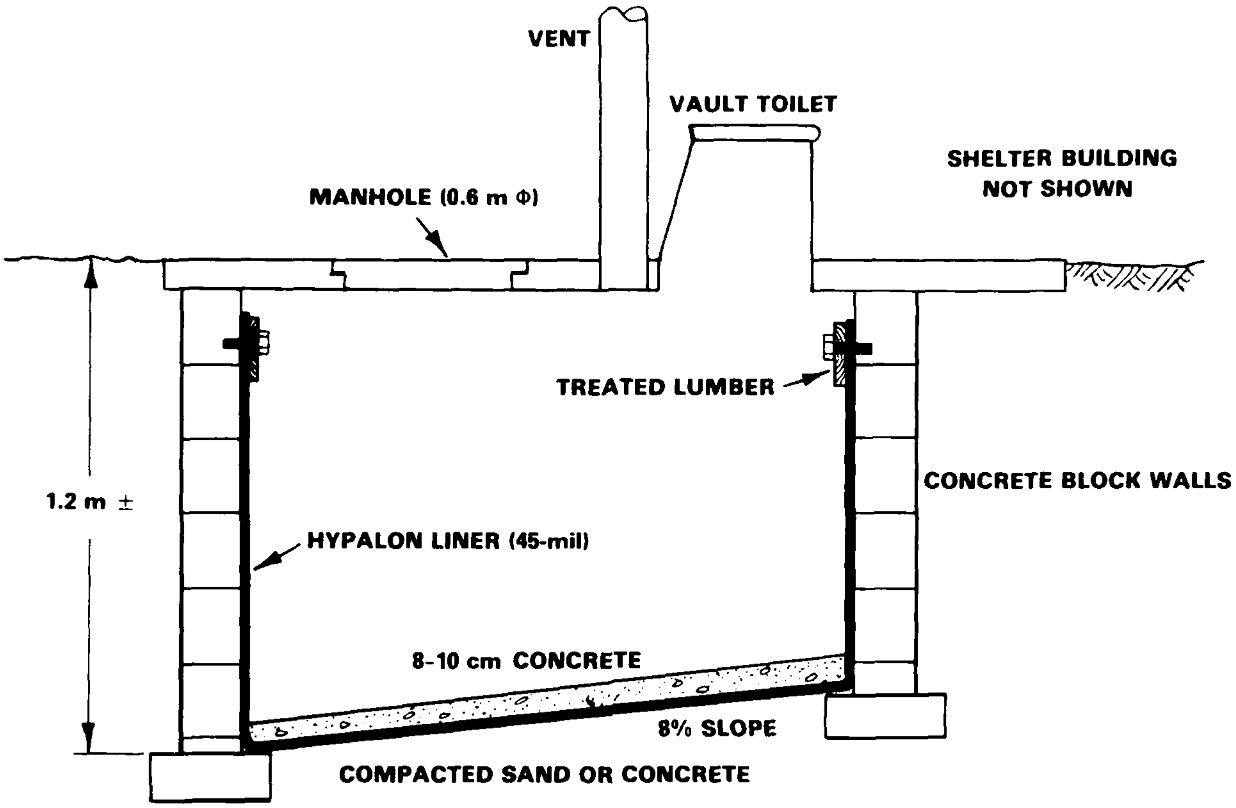


Figure 16. Vault toilet construction.

ity is warranted. A large-diameter manhole in the vault cover is essential for access during cleaning. The vault should be pumped out at the end of the recreational season or more frequently if necessary. Vault construction should not be used at sites with high groundwater, to avoid contamination and stresses due to buoyant forces on the empty tank. Some manual cleaning may be necessary, since all sorts of undesirable objects tend to find their way into the vault and cannot be removed with the typical pumper trucks.

On-Site Treatment

The most common form of on-site treatment provided is the conventional septic tank. Its principal functions are to serve as a primary clarifier and to separate scum and grease from the wastewater. Removal of these floating and settleable materials improves the effectiveness of the final disposal method. In warmer climates, the settled sludge undergoes some anaerobic digestion, so pump-out may be necessary only every 3-5 years. In cold regions, an annual sludge pump-out is more typical. Figure 17 illustrates the basic design concepts for typical septic tanks. The gravity flow type is

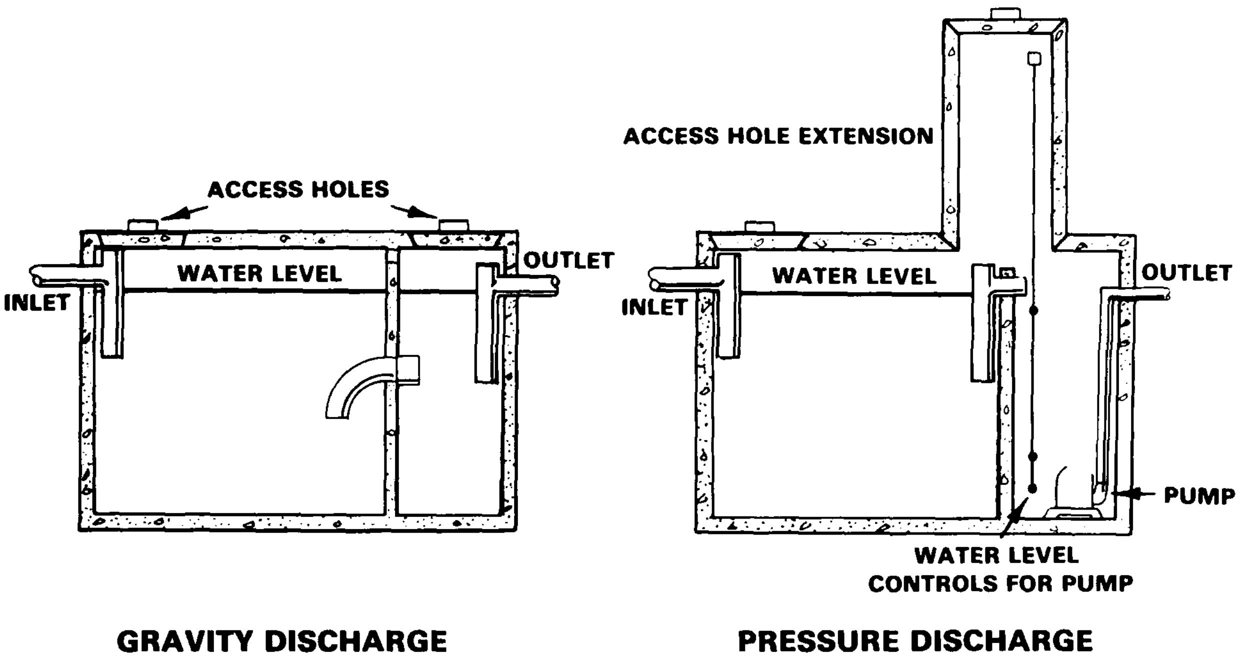


Figure 17. Typical two compartment septic tanks.

most common. The pressure discharge type is necessary for mound disposal systems, for most surface discharges, and for connection to pressure sewers as an alternative for in-house grinder pumps. The local regulatory authority will usually specify the volume of the septic tank required for the size of the house and/or the number of people served. For a typical single-family house, tanks range from about 2800 to 4700 L (USEPA 1980). Septic tanks for schools and similar isolated structures should be designed with the following equation:

$$V = 4200 + 0.75Q \tag{4}$$

where: V = tank volume (L)
Q = daily flow (L/d)

Septic tanks are typically buried, but where there is potentially unstable permafrost, they must be located above ground on suitable foundations and thermal protection must be provided for the tank, as described in a later section of this report. The most commonly used tanks are precast concrete units with 8- to 10-cm-thick walls waterproofed with a bituminous coating. Steel tanks have been used but they are susceptible to corrosion. Plastic tanks using polyethylene and fiberglass are available; they offer the advantages of light weight for easy transport and installation and corrosion resistance in place.

A variety of on-site aerobic treatment systems are available, varying in capacity from single family to institutional sizes. Treatment concepts include extended aeration, trickling filters, rotating discs (RBC), and upflow filters. The major advantage claimed for these units is the potentially higher level of treatment they provide, which in turn may permit a more effective final disposal or discharge step. In particular, it is claimed that seepage pits and leaching fields can have a smaller infiltration area when used with these aerobic units because the effluent contains less solids, reducing the potential for clogging. In some cases, direct discharge of these aerobic effluents to surface streams may be permitted.

All of these aerobic systems have mechanical elements and require routine maintenance on at least a monthly basis. In addition, excess sludge must be disposed of on at least an annual basis. For the biological process to operate at the design rates, aerobic units require more thermal protection than septic tanks. Most aerobic units require preliminary removal of gross solids (trash, grease, garbage grindings) and may use a trash trap or a septic tank for this purpose.

Aerobic units are sensitive to variations in the quantity of the flow and its composition. Their design must take into account the impact of water conservation measures on the composition of household sewage, which will reduce the volume of water while the mass of pollutants remains essentially the same. Table 8 lists the range of the pollutants of major concern in typical residential wastewater in a household with conventional fixtures and with no attempt of any kind to conserve water. Figure 18 illustrates the impact of water conservation on the concentration of these pollutants. A 30% flow reduction, for example, results in about a 45% increase in pollutant concentration.

Table 8. Typical residential wastewater composition

Constituent	mg/L
BOD_5	200-290
Suspended solids	200-290
Total nitrogen	35-100
Total phosphorus	18-29
Fecal coliform	10^8-10^{10}/100 mL

Table 9 compares the effluent concentration from septic tanks to that from aerobic units. These are the averaged values of a large number of test results from studies in both the United States and Canada (USEPA 1980). Aerobic units can remove more BOD and fecal coliforms than septic tanks, but not enough to eliminate concern; the level of BOD and suspended solids remaining may not allow the use of smaller disposal fields and pits. Under optimum conditions, aerobic units can produce an effluent comparable in quality to conventional secondary treatment. In practice, however, they are subject to variations in flow, in temperature, in wastewater composition, and in the degree of operation and maintenance attention, so the extra treatment achieved does not appear to justify their use when in-ground (seepage pit or leach field) disposal is intended. On the other hand, an aerobic unit is smaller and lighter than a septic tank and can more easily be installed within a dwelling if permafrost conditions prevent burial. The effluent is aerobic and should cause fewer odor and other aesthetic complaints for a surface discharging system. In general, the loss of solids with the final effluent

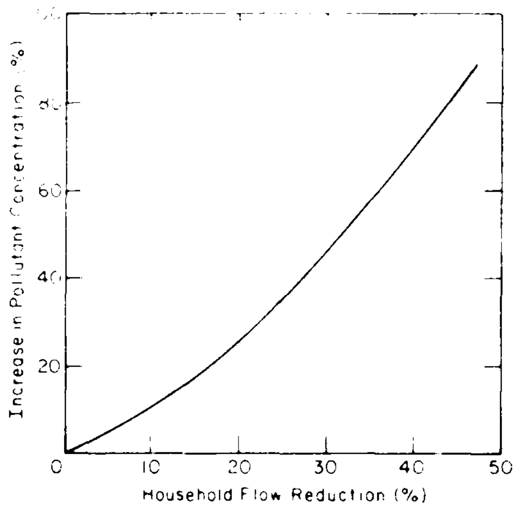


Figure 18. Flow reduction - pollution concentration.

Table 9. Typical effluent characteristics from septic tanks and suspended-growth aerobic units.

Constituent	Septic tank effluent (mg/L)	Aerobic effluent (mg/L)
BOD_5	140[a]	80[c]
Suspended solids	80[b]	83[d]
Total nitrogen	42	40
Total phosphorus	20	18
Fecal coliforms	10^6/100 mL	10^4/100 mL

[a] Average of 316 tests at 41 locations, range 7-480 mg/L
[b] Average of 319 tests at 41 locations, range 10-695 mg/L
[c] Average of 1038 tests in 7 studies, range 1-824 mg/L
[d] Average of 897 tests in 7 studies, range 1-768 mg/L

is the major factor that keeps these units from achieving their theoretical performance efficiency. If further research can solve that problem and maintain reliability with less maintenance, aerobic units will offer significant advantages in a number of situations.

On-Site Disposal

Direct discharge of the effluent from septic tanks or aerobic units is technically possible and is permitted by regulation in some locations. In most cases, such effluent from a single dwelling in a remote location has a negligible impact on the receiving environment. Protection of health is the major issue of concern both for the occupants of the source dwelling and for any adjacent populations. This requires that the impact of the disposal site on water and food supplies, as well as the potential for disease vectors (insects, birds, or animals), be taken into consideration. Figure 19 illustrates the design of an open surface discharge that is permitted for septic

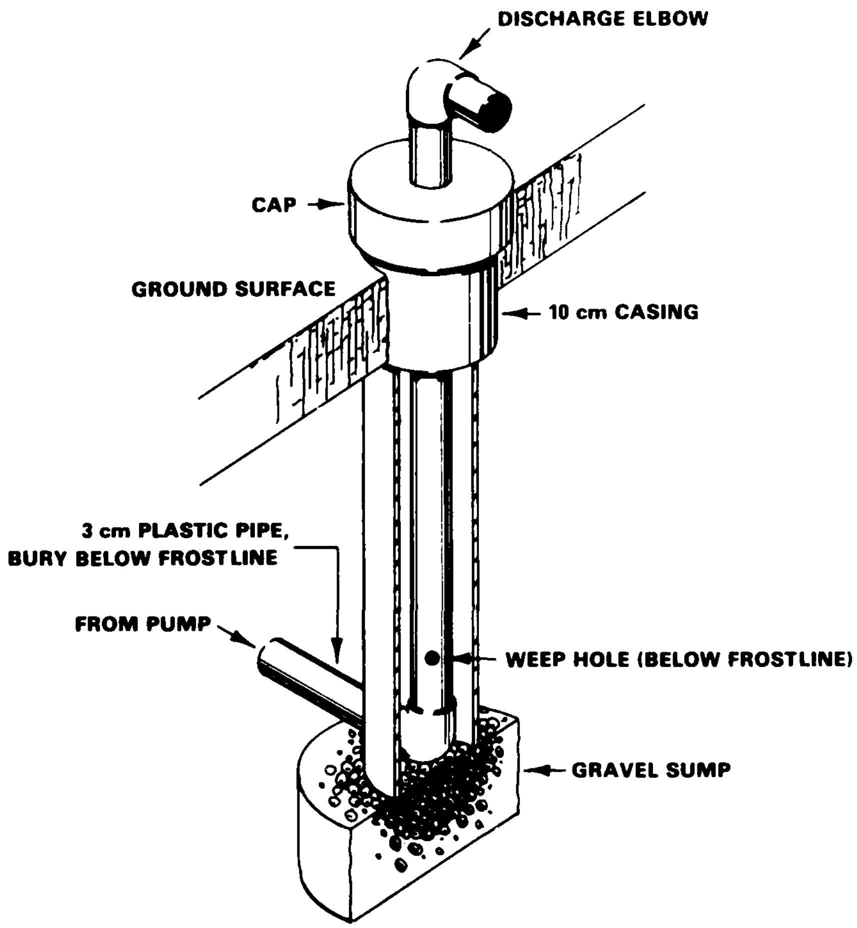


Figure 19. On-site open surface discharge.

tanks on farms in rural parts of Saskatchewan. The pump is in the second chamber of a pressure-discharge septic tank (Figure 17) or in the house. Float switches in the wet well are set to control the frequency of pumping and the amount pumped each cycle. For long transmission distances, it is not practical to have the entire pipe contents drain back into the wet well between pump cycles. In these cases, the pipe is laid below the frostline and a small weep hole is drilled in the riser below the frostline, so that any liquid in the riser will drain out between pump cycles. Any water remaining in the casing at the start of the next pump cycle will then be drawn back into the riser and discharged. It is necessary to insulate and heat-trace the pipe and riser at those locations where an unfrozen zone of soil does not exist in the winter months.

In the United States, intermittent sand filtration is commonly used where surface discharge of septic tank effluent is desired or necessary (USEPA 1980). It can be completely buried and inaccessible after construction or constructed at or above the ground surface for free access during operation. Figure 20 illustrates a typical free-access filter, constructed with two compartments that are used alternately for septic tank effluents. The effluents are applied at a rate of up to 0.2 $m^3/m^2/d$. The filter sand should have an effective size of 0.35-1.00 mm with a uniformity coefficient less than 4.0. The filter should be flooded at least twice a day to a depth of about 5 cm. Dual filters, as shown in Figure 20, each sized for design flow, are recommended for septic effluents. For aerobic pretreatment, a single filter sized for design flow is adequate, and the hydraulic loading can be double the value used for septic effluents. The effluent characteristics from these filters are quite good, with BOD ranging from 8 to 23 mg/L and suspended solids less than 10 mg/L (USEPA 1980).

A recent innovation adds recirculation to the intermittent filter unit, as shown in Figure 21. Better overall performance and better final effluent quality than single-pass filters are claimed as the major advantages. Recirculation ratios from 3:1 to 5:1 are commonly employed. The size of the recirculation chamber is normally 1/4-1/2 the volume of the septic tank. The pump should be set to operate 5-10 minutes every 30 minutes and flood the filter to a depth of about 5 cm. Filter media and other construction details for recirculating filters are similar to those described previously for single-pass units. A simple float valve, as shown in Figure 21, controls the filtrate flow, either back into the recirculation tank or out to discharge.

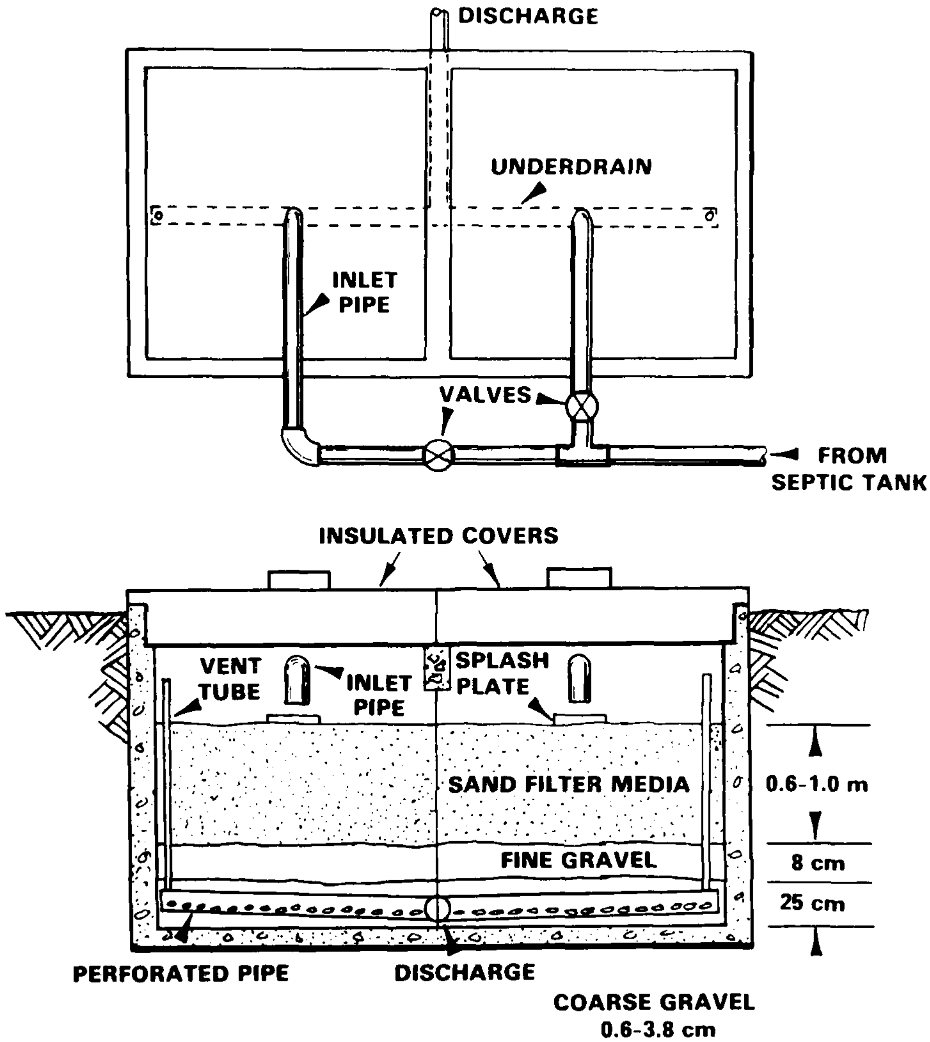


Figure 20. On-site wastewater filter.

Both types of filters require that the sand surface be raked about every 3 months and that the top 5-8 cm of sand be replaced when water ponds to a depth of 30 cm or more on top of the filter. The recirculating filter will function adequately if the surface layer is skimmed off when a heavy encrustation occurs and then new sand is added when the sand depth falls below 60 cm.

In-ground disposal of wastewater, either through leach fields or seepage pits, is the most commonly used technique in cold regions. Figure 22 illustrates the design concepts for a typical household leach field for a gravity discharge septic tank. The pipe is usually of plastic and is either perforated or laid with open joints. A pressure discharge system would have

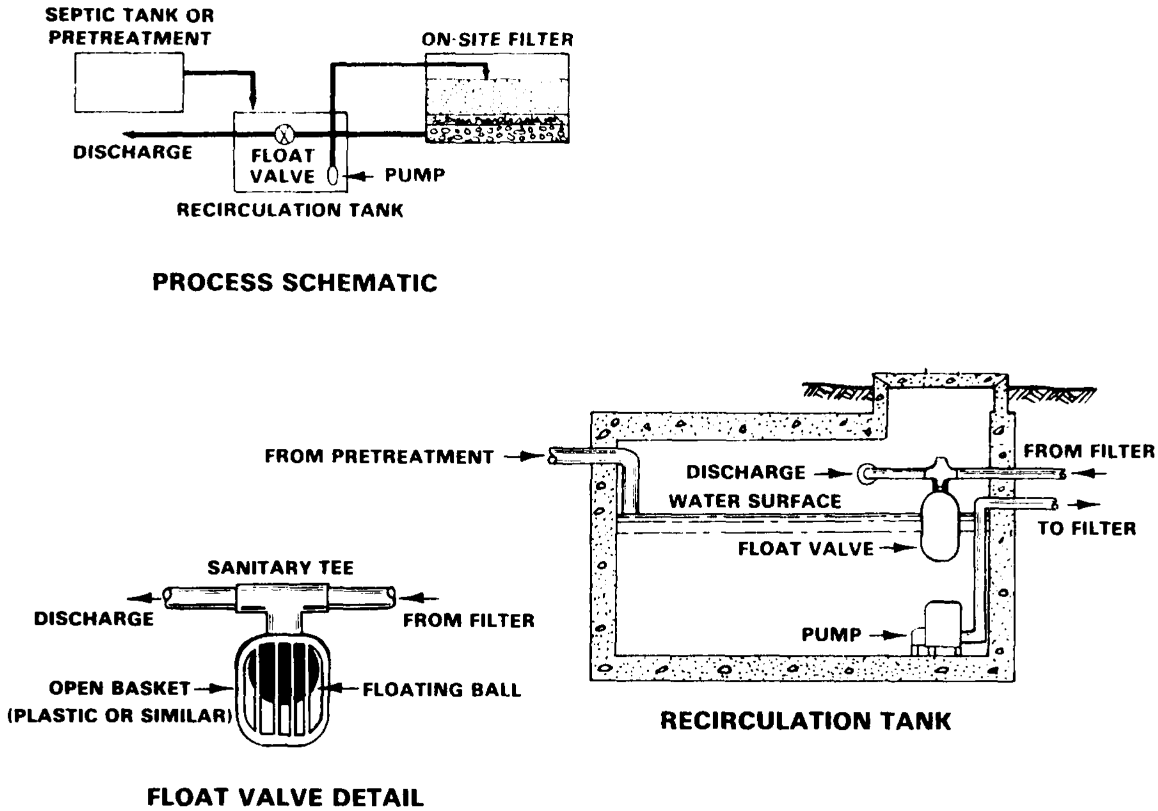


Figure 21. On-site recirculating filter.

smaller-diameter piping to ensure uniform distribution of wastewater each pump cycle. A typical pressure system might have an 8-cm manifold pipe connected to 4-cm perforated lateral pipes. The perforations drilled in the field might be 0.6 cm in diameter, located on 75 cm centers. Other details would be as shown in Figure 22. USEPA (1980) provides complete details on design of the pipe network for pressure discharge systems. For effective performance, the soil around and under the disposal fields must remain unfrozen throughout the winter. The heat in the wastewater will usually keep the soil from freezing in a continuously operated system. Problems can occur after long periods of non-use in extremely cold climates. Although the pipe and gravel bed should drain after each use, frost penetration into the in-situ soil can create an impermeable barrier. A natural or induced snow cover over the field area will act as an insulating blanket and maintain unfrozen conditions throughout the winter. In extreme climates with minimal snow cover the use of polystyrene insulation board over the trenches should be considered. The thermal aspects for design of on-site septic tanks, pipes, and leach fields are discussed in a later section of this report. Disposal fields have been used throughout Alaska and Canada with marginal

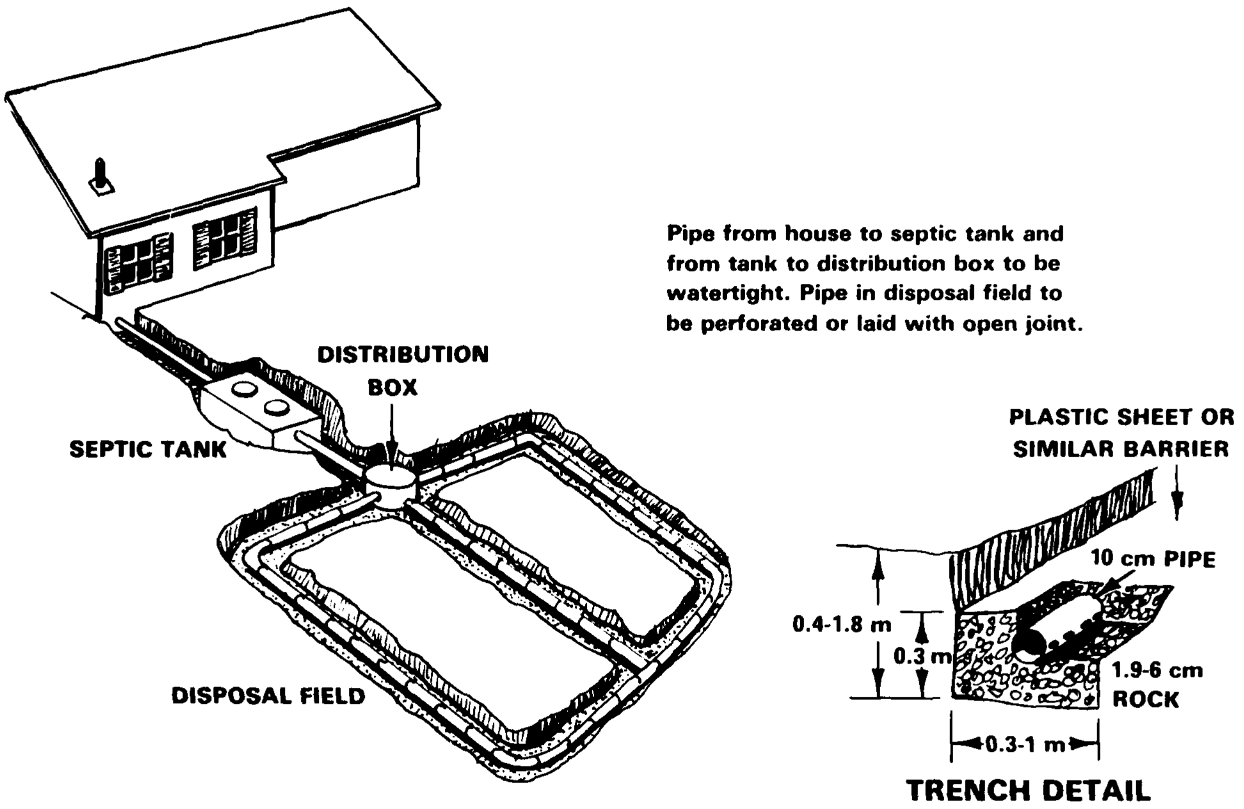


Figure 22. Typical septic tank system.

success. The failure rate in Alaskan communities (Fairbanks, Anchorage) is high. However, the typical failure is not due to freezing but to faulty design, faulty construction, carryover of solids from an improperly maintained septic tank, or excess infiltration of surface water due to improper site drainage. A common alternative to the trench system shown on Figure 22 is to install the distribution piping on a continuous bed of sand or gravel.

In much of Alaska a seepage pit is more commonly used than the conventional leaching field. It requires a deeper excavation than trenches or beds but it is more compact and has less horizontal surface area, so it has the potential of greater thermal efficiency. Figure 23 illustrates the typical construction details for a log seepage pit as used in Alaska. Perforated large-diameter concrete cylinders or concrete blocks installed with open joints are also used for pit construction. If more than one pit is needed, the space between them should be equal to about three times the outer diameter of the pit. Clogging will rapidly occur on the pit bottom, so the design is based on infiltration through the sidewalls of the pit. The design sur

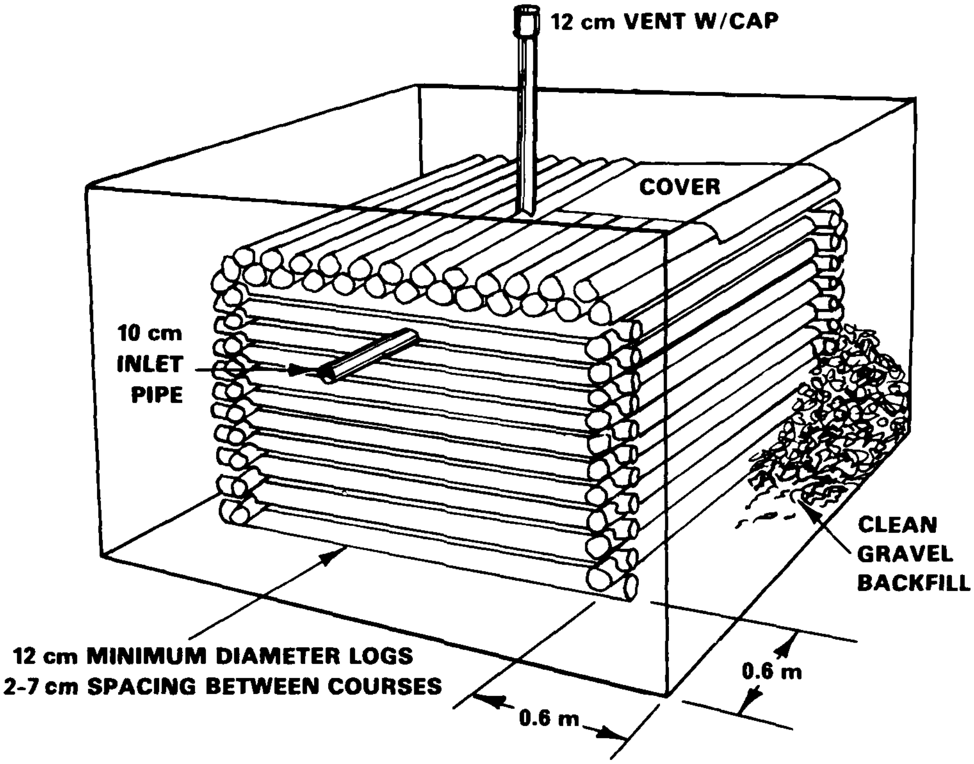


Figure 23. Typical log seepage pit.

face area is at the interface of the natural soil and the gravel or rock backfill.

The area required is determined from the percolation test results in the natural soil. If the soil profile is layered and has different percolation values, a weighted average should be used for design. If any layer has a percolation rate slower than 12 min/cm, it should not be included as a useable zone in the design calculation. Typically, pits are 2-4 m in diameter and 3-6 m deep. Other dimensions are possible and depend on soil conditions, the capabilities of the excavation equipment available, and thestructural stability of the construction materials for the walls and cover.

The surface area required for trenches, beds, and pits is usually based on simple percolation tests in the soil at the depth to be used in the system. Figure 24 illustrates the typical apparatus for the field test, and Table 10 summarizes the test procedure. Table 11 relates the wastewater application rates to the percolation test results and can be used for design.

Table 10. Percolation test procedure.

1. Conduct 3 or more tests in the area of concern at the depth of interest. Seepage pits in layered soils require a test in each layer to the full depth to determine the effective area.

2. The test hole is about 15 cm in diameter and at least 30 cm deep. It can be dug by hand or bored. Scratch the sides of the hole with a sharp instrument and place about 5 cm of gravel in the bottom to prevent scouring during the test.

3. Fill the hole with 30 cm of water for presoaking. In sandy soils with little or no clay the water will infiltrate in 10 min or less, and the test can proceed immediately. In soils with a significant clay content, soaking should continue for at least 4 hr by maintaining the 30-cm depth of water. This is to allow the clay soils to expand. Soaking should continue overnight for soils with a high clay content.

4. At the start of the test period, adjust the water level to 15 cm above the top of the gravel layer in the bottom. The water should not rise above this level during the test.

5. Measure the water level with one of the devices shown in Figure 24 at 30-min intervals to the nearest 0.2 cm. After each reading, readjust the level to the 15-cm level. Continue the test until two successive measurements do not vary by more than 0.2 cm. In coarse-textured soils where the initial 15 cm of water seeps away in 30 min or less, make the measurements at 10-min intervals (readjusting to the 15-cm level each time) for an hour. The last value is used for design.

6. The design rate for the area is determined by averaging the individual test results. Pit design is based on the weighted average with depth (summation of percolation rate × thickness of layers ÷ total thickness). For example, if the last measured drop after 30 min was 2 cm, the percolation rate would equal:

$$\frac{30}{2} = 15 \text{ min/cm}$$

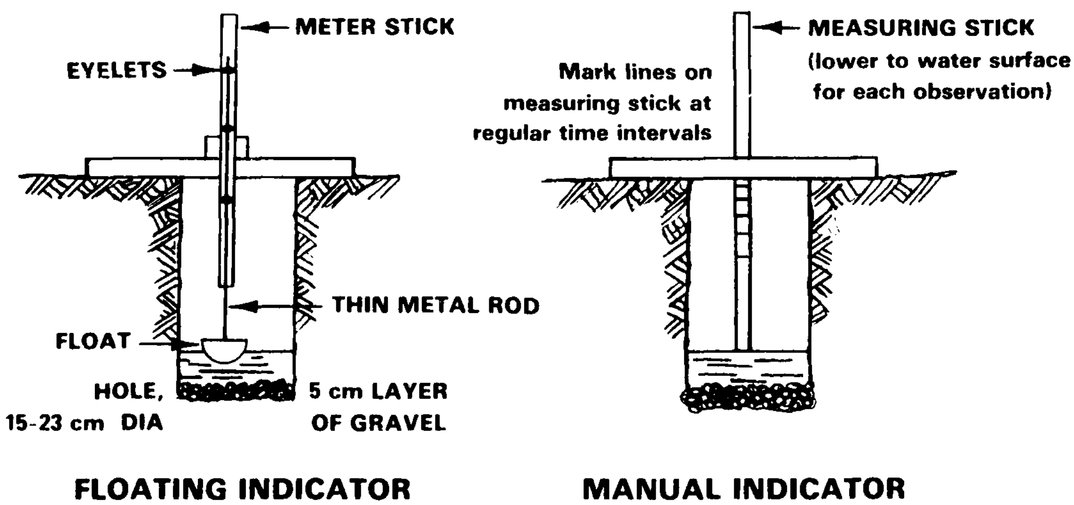


Figure 24. Percolation test apparatus.

Table 11. Wastewater application rates for conventional trench and bed disposal systems and seepage pits.

Soil type	Percolation rate (min/cm)	Design application rate ($L/d/m^2$)
Gravel, coarse sand	< 0.5	not suitable*
Coarse to medium sand	0.5 - 2	50
Fine sand, loamy sand	2 - 6	36
Sandy loam, loam	7 - 12	25
Loam, porous silt loam	13 - 24	20

*Flow rate too high for adequate treatment. Replace existing material with 60 cm sand or loamy sand.

For example, a percolation rate of 6 min/cm would allow a wastewater loading of 35 $L/d/m^2$ of infiltration area. A household with a 400-L/d design flow would require 11.4 m^2 of infiltration surface. This surface area is the sidewall of a pit system and the bottom area of a trenches and bed system. Some regulatory agencies allow design credit for at least a portion of the sidewalls in a trench system. Gravels and coarse sands are excluded in Table 11 since the water percolates through the material too quickly for adequate treatment to occur. In isolated remote locations where there is no possibility of water-supply contamination, this criterion can be relaxed. Soils with high clay contents will usually have percolation rates exceeding 24 min/cm and are not well suited to conventional pits, beds, or trenches.

Mound or raised-bed disposal systems may be suitable for clay soils or for sites with high groundwater tables or shallow bedrock. The principle involves raising the application bed a sufficient distance so that the larger base area of the mound serves as the design infiltration surface. Figure 25

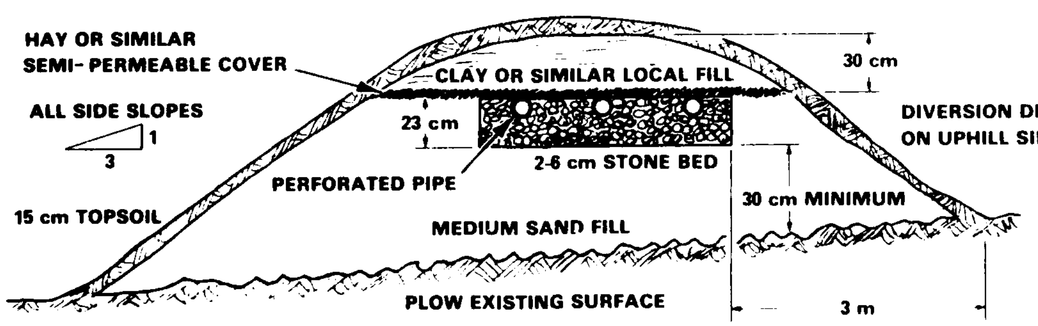


Figure 25. Typical mound construction.

demonstrates typical design details; many regulatory agencies have specific design requirements regarding size, slopes, and construction materials. The design requires a two-step operation: Run percolation tests in the natural soils on the site (Table 12 can be used to determine the base area of the mound); then, based on the type of soil used to construct the mound, determine the area of the application bed. Table 13 relates the most commonly used fill materials to the design rates for bed area. An alternative is to design the mound base area using Table 12, place the fill, allow it to consolidate for several months, run percolation tests in the consolidated fill, and use those values and Table 11 to design the application bed area. Pressure distribution is recommended for all mound systems even if topography would permit gravity flow from the septic tank to the mound. This is to ensure uniform distribution of wastewater over the entire application bed area.

Table 12. Infiltration rates for determining base area of mounds.

Soil type	Percolation rate (min/cm)	Design application rate (L/d/m^2 base area)
Sand, sandy loam	0 - 12	50
Loams, silt loams	13 - 18	30
Silt loams, silty clay loams	19 - 24	20
Clay loams, clay	25 - 47	10

Table 13. Infiltration rates for mound fill materials.

Material	Characteristics (% by weight)	Design rate* (m^3/m^2)
Medium sand	> 25%, 0.25 - 2.0 mm < 30-35%, 0.05 0.25 mm < 5-10%, 0.002 - 0.05 mm	0.049
Sandy loam	5-15% clay content	0.024
Sand/sandy loam mixture	88-93% sand 7-12% fines	0.049

* (m^3/m^2) x 24.54 = gal/d/ft^2

Off-Site Conveyance

In some cases the cold-region facility may be close enough for hook-up to the main sewer system, and/or a cluster of buildings may be tied into a remote disposal system. Gravity, pressure, and vacuum conveyance systems have all been successfully utilized in cold regions. Each requires special considerations at the house connection and for other internal requirements. See USEPA (1979) for details on central collection systems.

Gravity Collection

Figures 12 and 13 show typical service-line connections to a building for a cold-region gravity sewage system. The lines should slope at least 1-2% to the collection main, depending on soil stability. Of the two examples shown, it is better to go through the wall than through the floor. The former allows for more movement of the house without damage to the sewer service line and permits all house plumbing to be kept above the house floor.

Pressure Collection

If soil conditions and layout make a gravity collection system impractical, a pressure or vacuum system may be considered. Pressure sewage collection systems usually have sections that operate under gravity, and vice versa. A small pump-grinder unit in or near each building provides the motive force for the pressure system (see Figs. 26 and 27). The main advantage is that it is not necessary to maintain grades. The pipes can be at the surface or buried, and small movements due to frost heave or thawing will not affect the system's operation. Smaller-diameter collection lines can be used with a pressure system, and normal elevation differences throughout a community will not affect operation. Pressure collection lines can be sized to handle any number of connections.

There are no problems with infiltration of groundwater because the lines are under pressure; however, a leak in the sewer line, if not repaired, could contaminate other lines within a utilidor. Construction costs would probably be lower than for either a gravity or a vacuum system, but O&M costs would be greater than for a gravity system because of the number of pump-grinder units required. The O&M costs for the majority of the sewage collection system will be paid by the building owners as they pay for the electricity. In addition, if a unit fails because of lack of O&M, only one user suffers.

The collection lines must be sized to maintain a minimum of 1 m/sec scour velocity. The minimum size collection line is 3 cm, which would be the

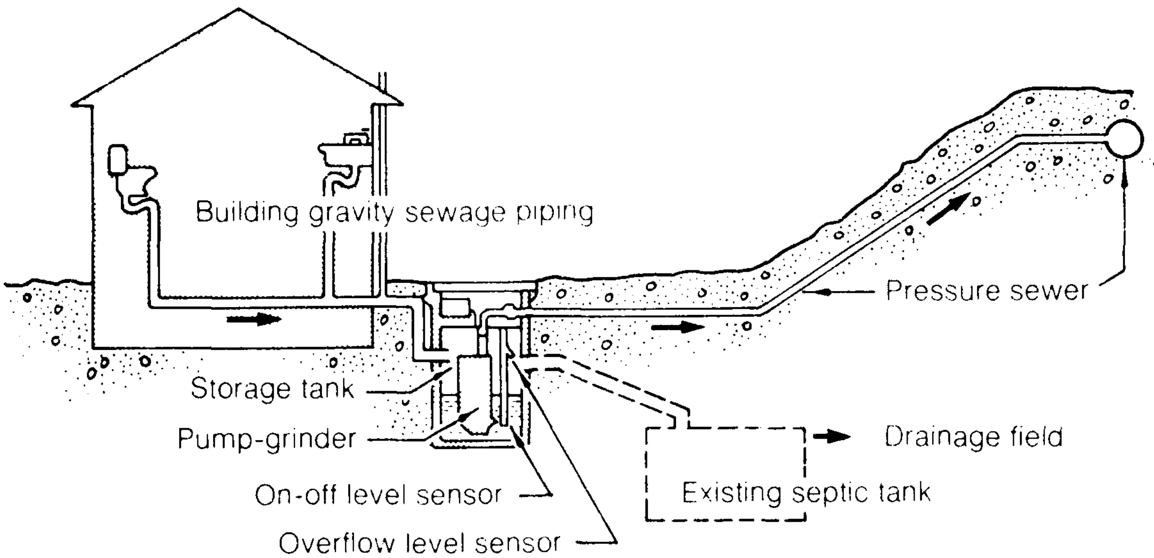


Figure 26. Typical pressure sewer installation.

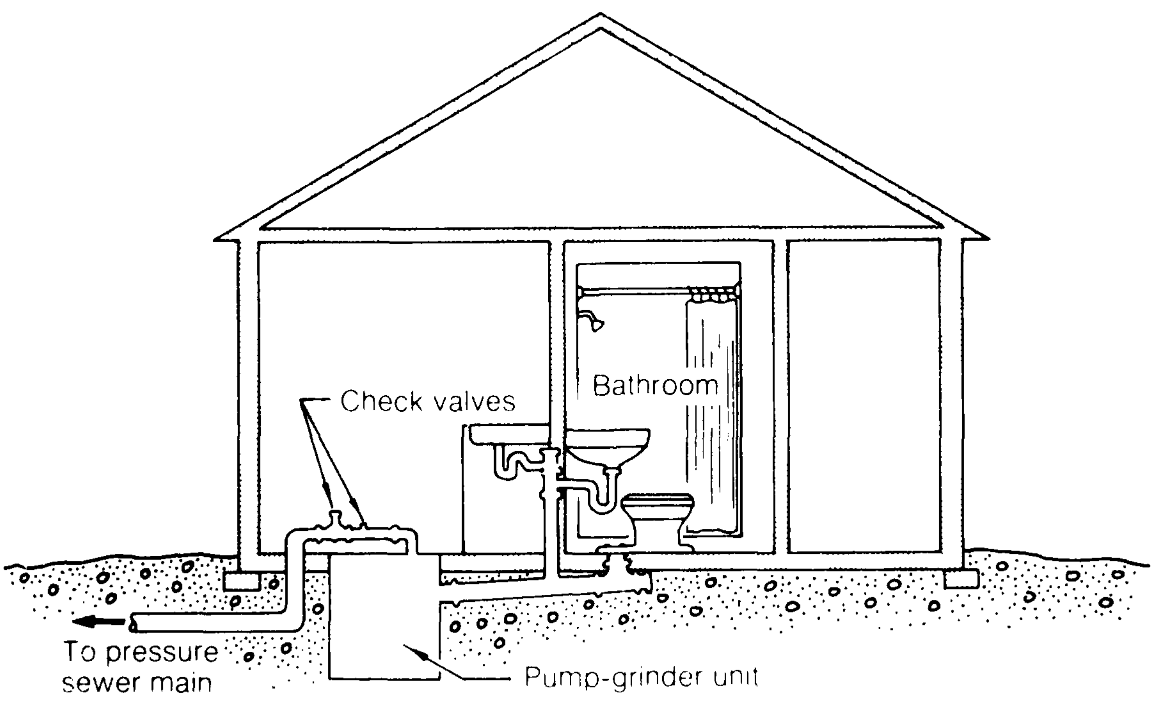


Figure 27. Typical pump-grinder installation.

size for one unit. If more houses are added than were originally planned for, velocities will increase down the line. The effect of this velocity increase is an increase in head loss, which, within reason, is not a problem because the individual pump-grinder units have a very flat pumping rate vs head curve. Pressures should be held below 275 kPa (40 psi) in the layout. The lines should be slightly undersized rather than oversized if the correct size is not available, to ensure a velocity of 1 m/sec. In the design of a pressure system, an assumption that 33% of the pumps will be operating at once is recommended for sizing pipes. The collection lines should be constructed to drain to low points if the system has to be shut down during the winter. In low flow conditions where heat losses may be extreme (such as at night in the winter in an above-ground situation) or where the minimum scouring velocity (1 m/s) cannot be met, the pressure collection lines should be looped back to a water source so warm water can occasionally be pumped through the lines. Air relief valves should be installed at major high points in the line.

The pump-grinder units can be situated in each building, or several buildings could drain into one unit by gravity. The units should be designed to pump against the design head in the main plus a 40% overload (with 33% of them operating at once). Each unit should have complete duplication of controls, sump pumps, and a pump or compressor for standby. The extra unit would take over if the primary unit were inoperable and, at the same time, set off a warning device (audible and visual) to alert the operator that repairs are required. For units serving several buildings, standby power should be available in case of a power outage. The pumping units should be well insulated and installed on a stable foundation if they are placed outside or in the ground, and they must be protected from frost-heaving forces. Double check valves should be provided on inlets and outlets to prevent backflow. This is especially important for pneumatic-type pump stations. Weighted check valves have proven more satisfactory than spring-loaded valves.

The pump-grinder units designed to serve individual buildings are equipped with positive displacement pumps that have a nearly constant pumping rate over a wide range of heads (Fig. 28). The grinder unit reduces objects to 6.5 mm size before they go into the pump. The unit must be able to handle items flushed down the toilets such as rocks, wash rags, and utensils. Positive displacement pumps also require a lower power input to purge the system

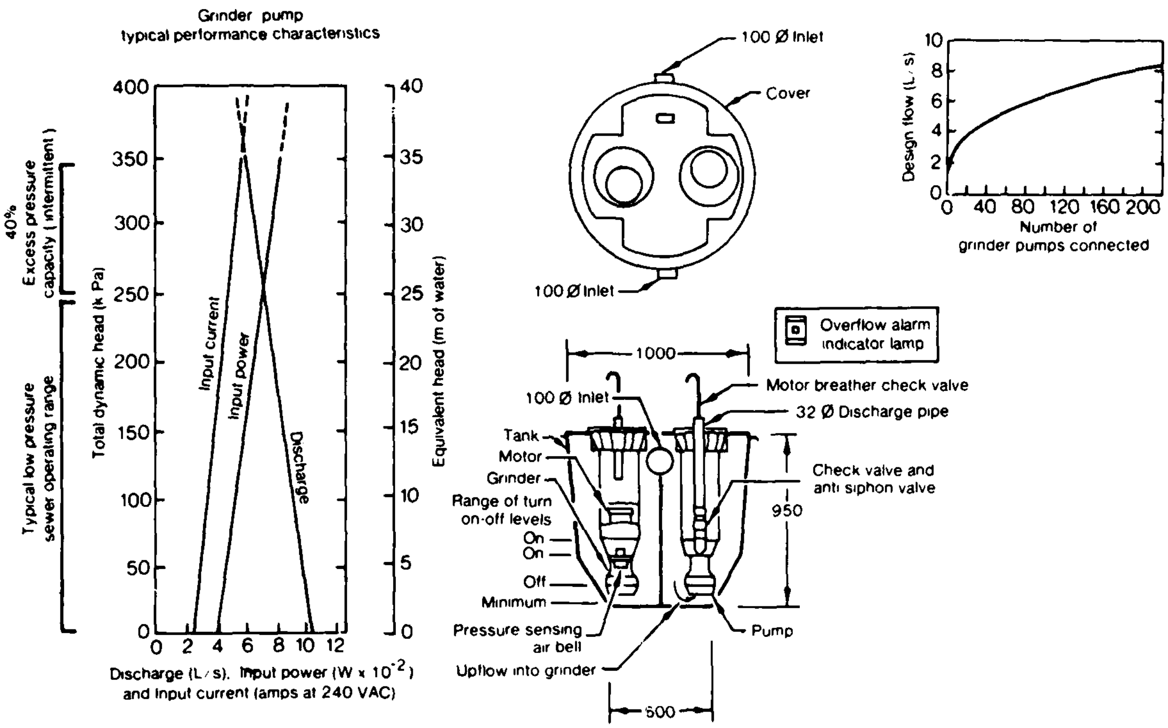


Figure 28. Pump-grinder characteristics (adapted from Environment/One Corp. Ltd.).

of air pockets that could form. The units must be small enough and light enough that they can be easily removed from the sump and repaired while the standby unit continues to operate.

With a 750 W (1 hp) pump-grinder unit and a water use rate of 190 L/capita/d (50 gal/cap/d), the pump would operate only about three times per person per day, with each operating period lasting about 1 minute. Thus, a five-person family would use about 0.5 kWh a day. At $0.25/kW, this would only amount to about $3.75/month per family for electricity.

The sump or tank from which the pump draws must be designed so that it is cleaned by scouring as the pump operates. The outlet check valves should be located in a horizontal run to prevent solids from settling out in them when the pump is not running. Pressure sensors should be used to control pumps and alarms because rags and grease tend to foul float switches. The sump should be sized (450-570 L) to provide several hours of storage in case of a temporary power outage or other problem. It is recommended that it be constructed of fiberglass or plastic to avoid corrosion.

The pump-grinder units and any compressors and pumps in larger lift stations should be supplied with low-voltage protection and a relay that will

stop the motors in case of a major voltage fluctuation. This device would also protect the motor if a rotor locks.

The pressure system can also be modified by using conventional submersible sewage pumps in holding tanks at each building. The tanks are similar to septic tanks where the solids settle, biodegrade anaerobically, and are occasionally pumped out by truck. The submersible pump moves the relatively clear effluent into the pressure sewer lines to a treatment facility. Some of the advantages of this type of operation are:

- Problems with plugging the grinder or the pump are eliminated.
- There are no solids to settle in the collection lines.
- The treatment facility is not as complicated as for conventional sewage.

Vacuum Collection

As with pressure systems, a vacuum sewage collection system is feasible only if soil conditions and community layout prevent the use of a gravity collection system. The vacuum system was developed in Sweden. Manufacturers and distributors in the U.S. and Canada should be contacted to obtain the latest design standards, as improvements are being incorporated continuously.

The vacuum sewer system is detailed in Figure 29. Toilet wastes, with a small amount of water, are transported through the pipes by the differential pressure between the atmosphere (air admitted to the system with the flushing action) and a partial vacuum in the pipe created by a central vacuum pump. A vacuum toilet (Fig. 30) only requires 1.2 L of water to flush, and the collection lines are small (5 cm). Vacuum systems are not limited to specific grades, but they are limited to 4.5-6 m in elevation differences because they are operated at 56-70 kPa (8-10 psi) vacuum (Averil and Heinke 1974, Rogness and Ryan 1977).

Leakage is essentially eliminated from vacuum sewage collection lines, and there is little possibility of sewage contaminating a water line in a utilidor. The flow conditions are slug-type, but the friction in the pipe breaks down the water slug. To reform the slug flow, transport pockets are required at intervals of about 70 to 100 m. The transport pockets (traps) are a disadvantage of the vacuum system: liquid will be standing in the traps for extended periods of time, so they must be well insulated or inside a heated space. They should also be provided with drains. The need for house vents and P-traps, with the freezing problems that accompany them, is eliminated.

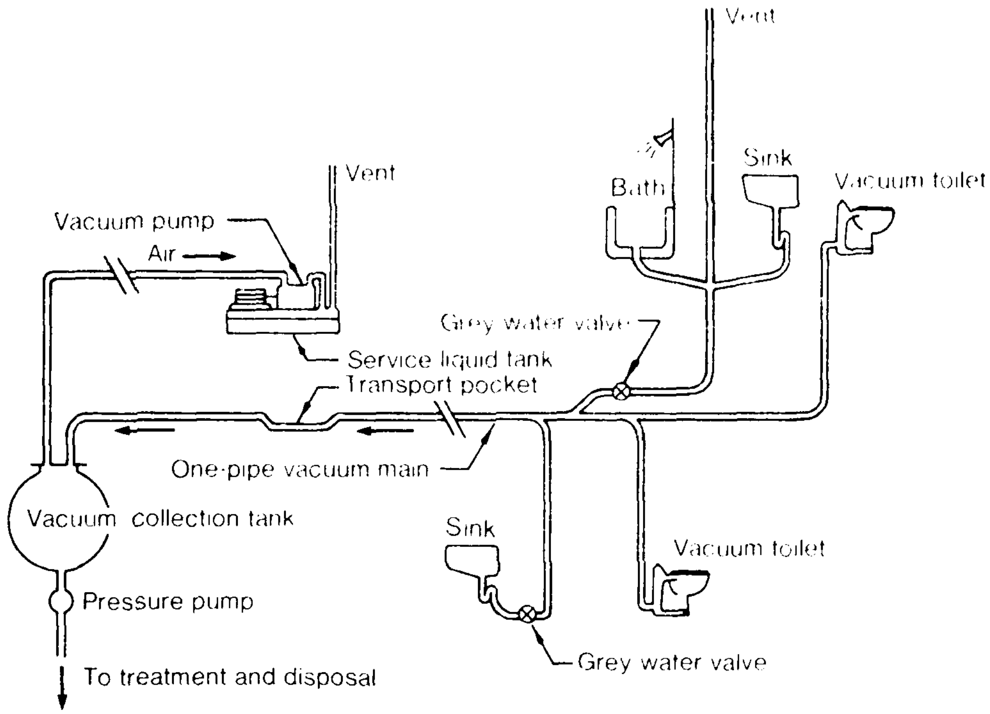


Figure 29. One-pipe vacuum system schematic.

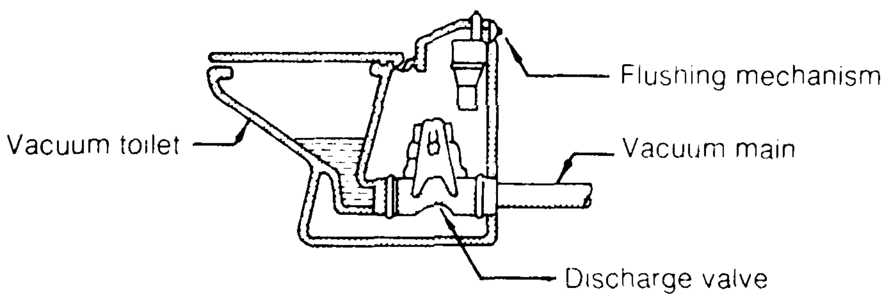


Figure 30. Vacuum toilet.

Vacuum systems can be used to collect sewage in large apartment buildings, but they are limited to 30-50 services on a given collection line. The collection line sizes will depend on the number of fixtures on a line and the estimated number that will be operating simultaneously. Usually 5- to 6-cm lines are used, with the traps dipping at least 1.5 pipe diameters. Tests have shown that head losses increase about 3.37 kPa (1 in. of mercury) for each 300 m of collection line with velocities of 4.5 m/s or less. Because the lines carry a combination of air and water, head losses are nearly impossible to compute. However, when going uphill, the increase in head loss is only about 20% of the actual elevation increase. Most fixtures will not

flush if there is less than 41 to 48 kPa (6 to 7 psi) vacuum in the collection lines. Thus, if several are flushing simultaneously and the vacuum drops to 41 to 48 kPa, additional fixtures will not flush until the vacuum is restored.

Grey water (sink, shower, and tub wastes) can be separated from black water (toilet wastes) for treatment or reuse by having the toilets on a different collection line from the grey water fixtures. In low-use lines where it is not desirable to have sewage stand in the traps for extended periods, an automatic or timed valve can be installed to bleed air into the end of the line and keep the wastewater moving. Full opening ball valves should be installed approximately every 60 m so that sections of the lines can be isolated to check for leaks or plugs.

A tank is located at the end of the collection lines. It is held under a vacuum at all times by liquid-ring vacuum pumps, which must be sized to evacuate the air and liquid admitted to the system by the users with a safety factor of two. In Noorvik, Alaska, the design criteria were six flushes per person per day for the toilets and 115 L/person/day for sinks and showers (Rogness and Ryan 1977). There were 50 houses on the system, so pumps were selected that were capable of evacuating 1.8 m^3/min at a vacuum of 53 kPa (16 in. of mercury).

The collected wastes are pumped out of the tank to the treatment facility using conventional centrifugal pumps. They must be designed to pump with a negative suction head equal to the maximum vacuum under which the tank must operate. The collection tank is sized similar to the pressure tank in a hydropneumatic system. One-half of the tank capacity is used for liquid storage and the other half is space (vacuum) serving as a buffer for the vacuum pumps. Several alarms should be included in the tank to give warning of high levels of sewage in the holding tanks, low incoming sewage temperature, and low vacuum in the system.

The plumbing fixtures in the building are the third important part of a vacuum system. The showers, tubs, sinks, and lavatories are conventional fixtures, but the addition of water conservation devices is recommended. The grey-water valve (Fig. 31) is activated by pressure from water upstream in the fixture drain line through a small pressure-operated diaphragm. As grey water drains from the fixture, it hits the closed valve and backs up against the diaphragm, activating it and allowing the vacuum in the collection main line to open the valve. A timer controls how long the valve is open. The

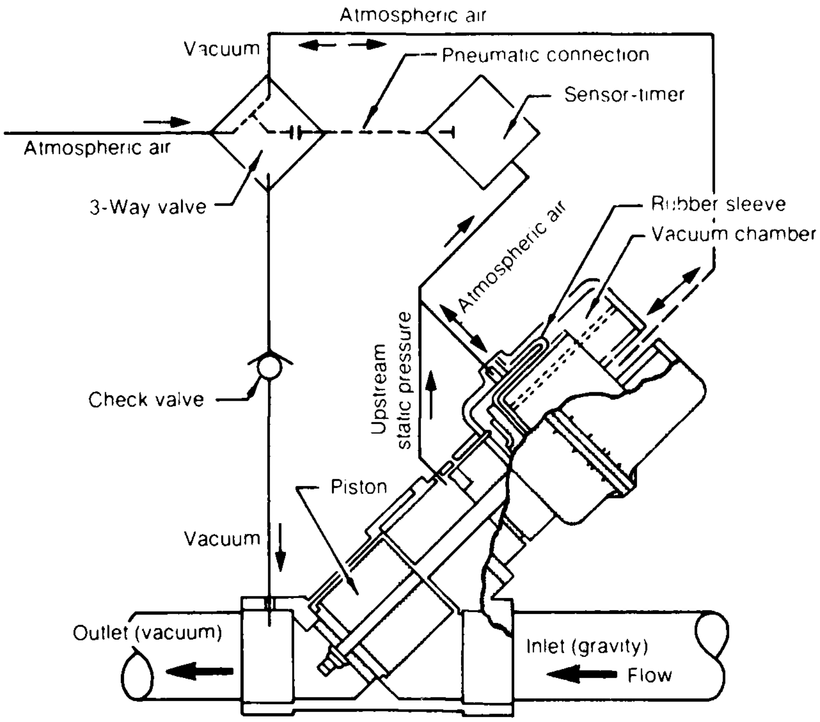


Figure 31. Grey-water valve.

cycle continues until no more grey water flows into the line and the fixture is empty. The grey water valves allow equal parts of air and liquid to enter the system (e.g. 115 L of waste and 115 L of air per person per day in Noorvik).

Vacuum toilets resemble conventional flush valve toilets. They are activated by pushbuttons that expose the waste in the unit to the vacuum in the main. The button activates the discharge valve and a water valve at the same time. The water valve allows about 1.2 L of water from the water system to enter the toilet bowl for cleaning purposes. The discharge valve closes shortly before the water valve, allowing a small quantity of water to remain in the toilet. The toilet discharge valve allows 100 parts of air per 1 part of liquid into the system, or 120 L of air per flush. The fixtures have been relatively trouble free for the 5 years they have been in operation at Noorvik, Alaska (Rogness and Ryan 1977).

SOLID WASTE MANAGEMENT

The proper on-site management of trash and garbage is obviously necessary for both health and aesthetic reasons. Detailed information on the

quantity and composition of solid wastes to be expected from households in remote communities in the Arctic and sub-Arctic can be found in USEPA (1979), along with information on household storage and on collection and disposal that is pertinent to on-site requirements.

The amount and characteristics of the household solid wastes generated are directly related to the occupants. Conservation measures to reduce the amount of solid waste produced can be marginally effective. Use (as fuel) or recycling of paper products (newspapers, bags) offers the most potential, but it is usually already a routine part of life at remote locations. Volume reduction prior to final disposal offers the greatest promise both for on-site disposal and for community haul systems. Two methods offer practical advantages used either alone or in combination.

If the trash and garbage can be at least partially segregated and the combustible material collected together, incineration in a simple open-top drum can reduce solid wastes by at least 50%. Air pollution from these burn barrels should not be a problem at isolated locations, and the practice can continue on a routine schedule year-round. The remaining incombustibles can be stored during the winter for on-site burial during the warm months, or they can be picked up routinely by a community disposal system.

Commercially available trash compactors can effect at least a 50% reduction in household solid wastes. When used for the combustible fraction after incineration, the final volume for disposal might be 10-20% of the original amount. This will be a significant benefit to either on-site or community landfill disposal operations. Burial is the preferred on-site disposal method, but the necessary excavation is usually only possible in the summer months. Temporary storage away from rodents and other vectors is therefore essential.

THERMAL DESIGN CONSIDERATIONS

The thermal aspects of design are a critical element in cold regions for water and wastewater pipes and for buried structures such as septic tanks, seepage pits, and leach fields. It is necessary to prevent freezing of the fluid in these systems, but where fine-textured, ice-rich permafrost is present it is also necessary to protect the stability of the foundation material. This latter situation imposes a design conflict, since heat is typically added to prevent freezing of the fluid but thawing must be prevented to maintain permafrost stability.

In the northern states of the contiguous U.S. it is typical practice to bury major utility service lines below the maximum depth of frost penetration. In the Arctic and sub-Arctic this may not be possible or economically feasible since the depth of frost penetration can easily exceed 3 m. In permafrost areas, frost penetrates all the way to the top of the permafrost layer, so no unfrozen material is available in the soil profile. In these cases insulation and/or heat addition is necessary. The criteria and examples given in this section demonstrate the design procedures required.

It is not typical practice to bury house service lines, septic tanks, and so forth below the maximum depth of frost penetration in the northern states. The continuous year-round usage establishes a warm zone in the soil around the unit and prevents freezing. In addition, a snow cover will provide insulation and retard frost penetration. As a rule-of-thumb, the depth of frost penetration is reduced by an amount equal to the thickness of the snow cover. The maximum depth of frost penetration occurs as a result of both the intensity of the cold and its duration. These effects are combined in a factor termed the freezing index (°C•d). Due to soil characteristics and moisture content, there is a time lag between the period of extreme low air temperatures at the ground surface and the maximum depth of frost penetration. In some cases the lag time may be a few months so that maximum depth of frost may occur in the spring after surface thawing has commenced.

The surface soil zone that freezes and thaws each year is called the active layer. In most northern areas it is common practice to bury the household utility services in this layer. This is usually acceptable in the northern U.S. unless there is no snow in a particularly cold winter or the building or facility is infrequently occupied, thereby reducing the heat input to the surrounding soil. In the Arctic and sub-Arctic it is typically necessary to insulate water lines and provide for emergency thawing. Insulation of septic tanks aids in heat retention and improves in-situ sludge decomposition, and the warmer discharge provides additional safety for the final seepage pit or leach field.

Insulation board above a leach field or seepage pit may be necessary to retard frost penetration. In theory, insulation board under a septic tank and leach field would protect the stability of the underlying permafrost. In a practical situation, however, if shallow, potentially unstable permafrost were present, a septic tank/leach field would probably not be feasible. The

Table 14. Thermal properties of common materials.

Material	Density (kg/m^3)	Specific heat	Thermal conductivity (cal/m•hr•°C)
Polyurethane foam	32	0.4	0.021
Polystyrene foam	30	0.3	0.031
Glass or rock wool	55	0.2	0.034
Snow, new, loose	85	0.5	0.07
Snow, drifted, compact	500	0.5	0.06
Ice at 0°C	900	0.5	1.9
Water at 0°C	1000	1.0	0.5
Clay, frozen (20% moisture)	1700	0.32	1.8
Sand, frozen (10% moisture)	2000	0.24	3.5
Wood (pine)	500	0.6	0.1
Concrete	2500	0.16	1.5
Polyethylene	950	0.54	0.31
PVC	1400	0.25	0.16
Steel	7500	0.12	37.0
Copper	8800	0.1	325.0

Note: cal/m•hr•°C x 1.1622 = W/(m•K)
cal/m•hr•°C x 0.6719 = BTU/hr•ft•°F

criteria and examples presented below demonstrate the design procedures required when insulation might be beneficial.

The calculations given below are based on the assumption that steady-state conditions prevail and that soil characteristics and moisture conditions are homogeneous. These simplifying assumptions allow relatively easy computational procedures that provide a reasonable approximation. The reader should refer to USEPA (1979), Thornton (1977), U.S. Army (1968), or Andersland and Anderson (1978) for more precise techniques or more complex situations (i.e. multiple-layered soil). Table 14 presents a list of the thermal properties of some common materials; see USEPA (1979) for a more complete listing.

Case 1. Insulated Pipe Above Ground in the Air.

For simplicity, ignore the thermal resistance of the pipe and the water and air films at the various interfaces (these are usually negligible for insulated pipe), and assume that the pipe is flowing full on a continuous basis.

The thermal resistance is

$$R_{ip} = \frac{\ln(r_i/r_p)}{2\pi k_i} \tag{5}$$

and the rate of heat loss is

$$Q = \frac{(T_w - T_A)}{R} \qquad (6)$$

where:

R_{ip} = thermal resistance per unit length ((m•K)/W or m•hr•°C/cal)

r_i = outside radius of insulation (mm)

r_p = outside radius of pipe (mm)

k_i = thermal conductivity of insulation (W/(m•K) or cal/m•hr•°C)

Q = rate of heat loss per unit length (W/m, or other consistent units)

T_w = water temperature (°C)

T_A = air temperature (°C)

All units must be consistent.

Example: Calculate the thickness of polyurethane insulation k_i = 0.024 W/(m•K) required around a 166 mm (6.5 in.) O.D. plastic pipe to maintain a water temperature of 5°C if the ambient air temperature is -40°C and the allowable heat loss is 13 W/m.

The insulation thickness is $r_i - r_p$.

$$r_p = \frac{166}{2} = 83 \text{ mm}$$

Substituting and rearranging the previous equations:

$$(r_i - r_p) = r_p \left[e^{2\pi k_i \left(\frac{T_w - T_A}{Q}\right)} - 1 \right] \qquad (7)$$

$$= 83 \left[e^{0.1532\left(\frac{5-(-40)}{Q}\right)} - 1 \right]$$

$$= 83 \, [1.6996 - 1]$$

$$= 58 \text{ mm } (2.28 \text{ in.})$$

Case 2. Buried Insulated Pipe

The thermal resistance of the pipe, R_{ip}, is the same as in Case 1 above and is given by eq 5 above. The thermal resistance of the soil is:

$$R_s = \frac{\ln \left[(H_p/r_p) + \sqrt{(H_p/r_p)^2 - 1} \right]}{2\pi k_s} \qquad (8)$$

$$\simeq \frac{\ln (2H_p/r)}{2\pi k_s} \quad \text{if} \quad H_p \geq 2\, r \qquad (9)$$

The rate of heat loss is

$$Q = \frac{T_w - T_G}{R_{ip} + R_s} \tag{10}$$

where:

R_s = thermal resistance of frozen soil ((m•K)/W or cal/m•hr•°C with other units consistent)

H_p = depth to center of pipe (mm)

r = outer radius of insulated pipe (mm)

k_s = thermal conductivity of frozen soil (W/(m•K))

T_G = air temperature at ground surface (°C)

The other terms are as defined in Case 1.

To prevent thawing of the surrounding soil, the temperature at the outer surface of the insulated pipe cannot exceed 0°C, and the necessary thermal resistance would be

$$R'_{ip} = \frac{(T_w - 0)}{(0 - T_G)} R_s \tag{11}$$

where:

R'_{ip} = necessary thermal resistance of pipe unit to prevent thawing of *the surrounding soil* ((m•k)/W *or* m•hr•°C/cal)

The other terms are as defined previously.

The insulation thickness $(r_i - r_p)$ required to prevent thawing is determined by combining the above equations:

$$(r_i - r_p) = r_p \left(e^{2\pi k_i R'_{ip}} - 1\right) \tag{12}$$

Example: Using the same pipe and temperature conditions described in the example for Case 1, determine the minimum thickness of polyurethane insulation required to prevent thawing of the surrounding soil if the pipe is buried 1 m (H_p = 1000 mm) below the surface in frozen clay (k_s = 2.092 W/(m•K)). Since H_p/r is essentially the same as H_p/r_p for the conditions specified, r_p (83 cm) may be substituted in the equation to determine R_s.

$$R_s = \frac{\ln(\frac{2000}{83})}{(2)(3.14)(2.092)} = \frac{3.1821}{13.138} = 0.242$$

$$R'_{ip} = \frac{5-0}{0-(-40)} (0.242) = 0.0303$$

$$(r_i - r_p) = 83\ [e^{(2)(3.14)(0.0244)(0.0303)} - 1]$$

$$= 83\ (1.004 - 1)$$

$$= 0.4 \text{ mm } (0.01 \text{ in.})$$

In effect, the pipe would need practically no insulation at all to prevent soil thawing under the specified conditions.

In the general case, it is likely that a thaw zone will develop around water and sewage pipes that are used on at least a daily basis when the ground surface is covered by snow. The thaw zone will be cylindrical, with its center typically slightly below the bottom of the pipe. The calculations are more complex since the properties of the thawed soil must be included; USEPA (1979) and Thornton (1977) should be used. In effect this zone of warmed soil represents a heat reservoir, which protects the pipe from freezing during short no-flow periods. Procedures in USEPA (1979) can be used to determine the time before freezing would occur in such a case.

Sewer pipes, leach fields, and seepage pits should drain between uses. However, if there has been a long period between uses (1 month or more) with little or no snow cover or a snow cover that has been compacted by traffic, subfreezing temperatures may penetrate to a critical depth and freezing might occur with the first increments of wastewater discharged at the next use. In these cases, a large initial discharge of hot water is recommended.

Case 3. Buried Septic Tank

Septic tanks are available in a variety of sizes and shapes. The most commonly used is a rectangular concrete tank. USEPA (1979) can be used for a more exact solution to thermal calculations for the actual shape involved. A reasonably accurate approximation can be obtained by assuming the tank is a cylinder of the same length with a surface area equal to that of the real tank. It is also necessary to assume that the tank is full and that wastewater is flowing through the unit at an average velocity based on the mean daily usage. Adoption of these assumptions then permits the use of the equations presented in Case 1 and 2 above or in USEPA (1979) and Thornton (1977) for relatively easy thermal calculations. One of the major concerns is to determine the effluent temperature leaving the septic tank:

$$T_2 = T_e + (T_1 - T_e)(e^{-1/qCR}) \qquad (13)$$

where:

T_2 = effluent temperature leaving tank (°C)

T_e = temperature at exterior surface of tank (°C)

T_1 = influent temperature (°C)

q = average daily flow rate (m^3/d)

C = volumetric heat capacity of fluid (assume water = 1000 cal/m^3•°C)

R = contained thermal resistance of buried unit (m•d•°C/cal)

Since the tank is buried, the thermal resistance is the sum of the bare or insulated tank and the resistance of the surrounding soil (see Cases 1 and 2 above).

<u>Example:</u> Assume an uninsulated concrete tank (walls 10 cm thick, 3 m long, 2 m deep, 1 m wide) with about 6 m^3 (1500 gal) capacity. The top of the tank is buried 0.3 m below the ground surface. Raw sewage enters the tank at 15°C. The design flow is from 8 people at 240 L/capita/d or an average 1.92 m^3/d. Determine the soil temperature at the tank surface that will result in an effluent temperature of 7°C (which is the minimum design temperature assumed for transmission to the leach field).

First, figure the surface area of the tank sides:

$$\begin{aligned} \text{Walls} &= (2)(2)(3) = 12 \\ \text{Roof and floor} &= (2)(1)(3) = \underline{\ 6\ } \\ & \qquad\qquad\qquad\ \ 18\ m^2, \end{aligned}$$

and the diameter of an equivalent cylinder (3 m long)

$$(\pi)(D)(3) = 18\ m^2$$

$$D = \frac{18}{(3.14)(3)}$$

$$= 1.91\ m\ .$$

From this we can figure the area of the cylinder ends:

$$(2)(3.14)(0.955)^2 = 5.73\ m^2.$$

The total surface area is 18 + 5.73 = 23.73 m^2. Now determine the thermal resistance of the tank:

$$\text{Resistance} = \frac{\text{material thickness}}{(k)\ (\text{surface area})} \qquad (14)$$

As stated, the wall thickness is 0.1 m. From Table 14, thermal conductivity k is (1.5 cal/m•hr•°C)(24 hr/d) = 36 cal/m•d•°C, so

$$R_{tank} = \frac{0.1}{(36)(23.73)} = 0.00012°C\cdot d/cal.$$

Assume the top of the cylinder is at the same depth as the top of the actual tank (0.3 m). Then H, the depth to the center of the cylinder, is

$$0.3 + 1.91/2 = 1.26 \text{ m.}$$

The outer radius of the cylinder is 1.91/2, or 0.955. Using a form of eq 8, the thermal resistance of the soil around the tank is

$$R_s = \frac{\ln\left[(H/r) + \sqrt{(H/r)^2 - 1}\right]}{2\pi k_s (L+D)} \qquad (8a)$$

From Table 14 the thermal conductivity, k_s, of frozen clay is 1.8 cal/m•hr•°C, or 43.2 cal/m•d•°C. The cylinder length and diameter (L+D) are 3 + 1.91 = 4.91.

$$R_s = \frac{\ln\left[\left(\frac{1.26}{0.96}\right) + \sqrt{\left(\frac{1.26}{0.96}\right)^2 - 1}\right]}{(2)(3.14)(43.2)(4.91)}$$

$$= 0.00058°\text{C}\cdot\text{d/cal}$$

$$R_{comb} = 0.00058 + 0.00012 = 0.0007°\text{C}\cdot\text{d/cal}$$

Equation 13 determines the temperature of effluent leaving the tank:

$$T_2 = T_e + (T_1 - T_e)(e^{-1/qCR})$$

$$e^{-1/qCR} = e^{-1/(1.92)(1000)(0.0007)} = 0.48$$

To find the tank surface temperature (T_e) when T_2 = 7°C and T_1 = 15°C:

$$T_e = 7 - (15 - T_e)\ (0.48)$$

$$= -\ 0.4°\text{C} \quad (31°\text{F})$$

To find the tank surface temperature (T_e) when the effluent temperature (T_2) is 0°C

$$T_e = 0 - (15 - T_e)(0.48)$$

$$= -13.8°\text{C} \quad (7°\text{F})$$

Since frost can penetrate several meters deep in the Arctic and sub-Arctic, a temperature at the surface of the tank of -13.8°C is quite possible. Additional thermal protection can be provided by deeper burial, higher flow rate (i.e. smaller tank), or insulation. An insulation of 2.5-cm-thick

polyurethane (k_i = 0.021 cal/m·hr·°C) would increase the tank's thermal resistance by at least an order of magnitude. In the above example the effluent would not freeze until the temperature at the tank surface reached -67°C (-89°F), which is unlikely to ever occur. The calculation procedures demonstrated above can be repeated for various combinations of surface temperature and insulation thickness to find the optimum. For simplicity, film resistances at the tank are ignored and, for insulated tanks, only the thickness of the insulation is considered.

Case 4. Frost Penetration and Leach Fields

The depth of frost penetration (i.e. 0°C isotherm) can be estimated with the Stephan equation, which is valid for a homogeneous material with a step change in the surface temperature:

$$X = \frac{\sqrt{2kF_I}}{M} \tag{15}$$

where:

X = depth of frost penetration (m)

k = thermal conductivity of the material above the freezing isotherm (cal/m·hr·°C)

F_I = freezing index (°C·hr or °C·d)

M = latent heat of the material (soil moisture) being frozen (80 cal/kg for water)

This equation can be expanded for a two-layer system involving a snow cover or an insulation board above the soil, where the upper material has no latent heat:

$$X = \sqrt{\left(\frac{k_2}{k_1}d_1\right)^2 + \frac{(2k_2)(F_I)}{M}} - \left(\frac{k_2}{k_1} - 1\right)d_1 \tag{16}$$

where:

k_1 = thermal conductivity of surface layer (cal/m·hr·°C)

k_2 = thermal conductivity of lower material (cal/m·hr·°C)

d_1 = thickness of surface material (m)

The other terms are as defined previously.

More complex multilayer systems involving snow and ice and different layers of soil require a more involved procedure. The modified Berggren equation described in USEPA (1979) is perhaps the most commonly used.

Example: Determine the depth of frost penetration under 8 cm of polystyrene board (k_1 = 0.031 cal/m·hr·°C) in a sandy soil (dry

density 2000 kg/m^3, 10% moisture, k_2 = 2.8 cal/m·hr·°C for unfrozen soil) when the freezing index is 3000°C·d.

The moisture content in the soil is 200 kg/m^3 (10% of 2000 kg/m^3). The latent heat of the soil is

$$M = (80 \text{ cal/kg})(200 \text{ kg/m}^3) = 16{,}000 \text{ cal/m}^3$$

The freezing index is

$$F_I = (3000)(24) = 72{,}000°\text{C·hr}.$$

Using equation 16,

$$X = \sqrt{\left(\frac{2.8}{0.031}0.08\right)^2 + \frac{(2)(2.8)(72{,}000)}{16{,}000}} - \left(\frac{2.8}{0.031} - 1\right)(0.08)$$

$$= \sqrt{52.2 + 25.2} - 7.15$$

$$= 1.65 \text{ m}$$

Under the specified conditions the depth of frost penetration would be about 5 m if the insulation board were not present.

Thermal calculations are more complex for a leach field since it represents a multiple-layer system (snow, frozen soil, perhaps insulation board, then unfrozen soil and the pipe with intermittent flow and heat input). The modified Berggren equation in USEPA (1979) should be used to find the solution. Clark and Williams (1983) have presented the results of thermal calculations for trench-type leach fields for site and operational conditions typical of the Anchorage, Alaska, area. As a general rule-of-thumb, 5 cm of polystyrene board insulation is roughly equivalent thermally to 1.2 m of sand or silt or 0.9 m of clay backfill over a buried pipe.

CONCLUSIONS

This report presents guidance and criteria for the planning and design of on-site utility services for remote military facilities in cold regions.

The unique design requirements of cold regions include: extreme low temperatures, long duration of cold periods, presence of permafrost and/or deep frost penetration, difficult site access, and rapid turnover of operational personnel. The procedures and concepts described in this report for water supply, plumbing, and waste collection, treatment, and disposal have been drawn from successful experience in the Arctic and sub-Arctic where these unique conditions prevail and therefore should be applicable to military facilities in similar or less adverse situations.

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